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Research article

Mechanical properties of sisal-epoxy composites as functions of fiber-to-epoxy ratio

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Abstract: Low density, low cost, environmental compatibility, wide availability, and high mechanical performance of raw materials are some considerable advantages of natural fiber composites. Sisal, very common type of natural fiber, is abundantly available in Ethiopia. This research aims to investigate mechanical properties of sisal reinforced composites such as tensile, flexural and impact strength. Fabrication of samples used the hand lay-up process with 15, 25, 30, 35, and 40 wt% sisal fiber to epoxy ratio. Tests for the properties indicated were made using the instron material testing system. Test results demonstrated, among the samples, that 30 wt% of sisal fiber-reinforced composites have the maximum tensile and flexural strength of 85.5 MPa and 85.79 MPa respectively. The impact strength has been found to be maximum for 40 wt% sisal fiber which is 24.5 kJ/m^2. As the result show, and compared with other researcher findings, the mechanical properties are acceptable as substitutes for applications demanding low-cost engineering applications such as automotive internal parts including interior door panel, back seat and body panels.

Keywords: sisal fiber-reinforced; epoxy; hand lay-up method

1. Introduction

Natural fibers have several advantages compared with synthetic fibers for reinforcement of polymer composites. They have low density, are biodegradable, abundant, non-abrasive, possess high mechanical performance and lack of toxicity [1–6]. Natural fibers such as kenaf, sisal, banana, jute, flax, hemp, curaua, and coconut are attractive alternatives to synthetic fibers [7,8] for applications in the automotive and construction industries. Mechanical performance of a fiber-reinforced composite depends on the integrity of the fiber/matrix interface which enables the strain from the matrix to the fiber. The strain transfer effectiveness plays a dominant role in determining the mechanical properties of the final product.

Among the various natural fiber composites, sisal fiber-reinforced composites produce superior impact strength with moderate tensile and flexural properties [2], making them potential alternatives for applications that require good impact strength. Currently, sisal fiber has been used as a reinforcement in variety of thermoset, thermoplastic and bio-degradable polymer composites and their mechanical properties like stiffness tensile strength, compressional strength, flexural strength and impact strength have been evaluated. Sisal fiber obtained from the sisal plant (known formally as Agave sisalana) is one of the most widely used natural fibers in various applications and can be easily cultivated in many parts of the world. The sisal plant grows about 100–200 leaves during its lifetime, and each leaf contains long, straight fibers which can be extracted using specialized processes. For this study, natural fiber composites, produced from sisal and epoxy available in Ethiopia, are investigated. Sisal plant is chosen for this research due to its wide abundance in Ethiopia as well as its lower cost as compared to synthetic fibers. Sisal fibers have additional benefits of being high strength to weight ratio, more environmentally benign than synthetic fibers and potentially pose less of a health risk to users [8]. Commercial use of sisal fibers in Ethiopia also has economic advantage by supporting industries that use sisal fiber composites.

The mechanical and chemical properties of sisal vary depending on source location, age of the fiber and method of extraction utilized. The principal components of sisal plant fiber are cellulose, hemicelluloses, waxes, pectins, mineral matter, and water. The sisal fiber is primarily made up of cellulose. The cellulose chains are firmly ordered and directed, which enables the sisal plant cellulose a high degree of crystallinity and results in good resistance to chemical and physical agents. Cellulose and lignin are the main chemical properties which are easily affected by environmental and manufacturing processes. Previous researchers have investigated the mechanical properties of sisal fiber as functions of various alkaline treatment strategies and manufacturing parameters. Kaewkuk et al. [9] reported that tensile strength and Young’s modulus increase as fiber content increases from 10 to 30 wt%. Dwivedi and Chand [10] also reported that the use of coupling agents during the manufacturing process improves mechanical properties and influences the wear resistance. According to Mylsamy and Rajendran [11], sisal fiber/epoxy composites having a fiber length of 3 mm have better wear resistance than those with 5- and 7-mm fiber length. Fiber pre-treatment and fillers are reported to improve fiber tensile strength and hardness, as reported by Oladele et al. [12] and Ismail et al. [13]. The effects of fiber modification and fiber loading on the mechanical properties, morphological and water absorption characteristics of sisal fiber/polymer composites are discussed by Khan et al. [13].

The specific objective of this work is to find the impact of fiber concentration and orientation [14,15] on the mechanical properties of sisal fiber-reinforced composites. In this research, sisal-epoxy composites of various proportion and fiber orientations are tested to determine tensile, flexural and impact properties.

2. Materials and method

2.1. Manufacturing process

To make sisal-epoxy sample plates, the hand lay-up techniques are used. Sisal fibers are extracted from the sisal plant leaves by hand using a knife. The fibers were washed and separated until individual fibers are clearly identifiable, then sun-dried and cut to a length of 300 mm. Alkali treatment using 10% NaOH was employed to enhance the adhesion property of sisal epoxy fiber [16], improving the mechanical behavior of the composite [17]. In this treatment, the fibers are soaked in NaOH solution for 3 h and then washed using distilled water to remove the traces of NaOH. The fibers were dried-up by being left outdoors for 48 h.

A steel mold having a dimension of 290 × 200 × 7 mm is used to prepare sample plates. Polymer matrix was prepared from epoxy system #2000 combined with system #2060 hardener which enables its mechanical properties to be shown on the material safety data sheet. The epoxy in liquid form is mixed thoroughly with the prescribed hardener and poured into all the layers of sisal fibers while being placed onto the mold and made to spread uniformly manually. A roller was used on each layer to remove any trapped air and excess epoxy while applying a mild pressure. A plastic sheet is placed over the top fiber layer, and it places release gel on the inner surface of the top mold plate. A 5 MPa pressure is then applied to press and cure the sample at room temperature for 24 h.

After curing, the sample plates are cut into test specimens according to the applicable ASTM standards for each case as presented in Table 1. To study the influence of sisal fiber content, composites are prepared with various weight ratios of fiber-to-epoxy and several fiber orientation patterns. The weight percentages of sisal fibers used in this study are 15, 25, 30, 35 and 40 wt%, with epoxy being the remaining constituent. Fiber configuration in each layer is random or alternately aligned layer-to-layer in the form of (0, 90, 90, 0) or (0, 45, −45, 0) degrees.

Table 1. ASTM standards used for the tests.

Test	ASTM standard	Procedure or test method (if applicable)	Specimen type/specifications (if applicable)	Deviations from ASTM standard
Tensile [18]	D638-14, standard test method for tensile properties of plastics		Type I	No extensometer used. Nest speed is 10 mm/min. No toe compensation made.
Flexural [19]	D7264/D7264M-07, standard test method for flexural properties of polymer matrix composite materials	Type A	Ratio: 32:1	Crosshead displacement issued as extension.
Impact [20]	D256-02, standard Test methods for determining the Izod pendulum impact resistance of plastics	Test method A		

3. Results and discussions

3.1. Characterization of material properties

Tensile, flexural and impact tests are conducted for each sample plate, as listed in Table 2. Specimen designation is based on fiber content and orientation (e.g., 15% sisal, 85% epoxy, random orientation is designated as R 15:85). Five test specimens are cut for each of the required tests from each type of sample plate.

Table 2. Samples and tests required.

Fiber ratio and orientation	Test type
R 15:85	Tensile, flexural, impact
R 25:75	Tensile, flexural, impact
R 30:70	Tensile, flexural, impact
R 35:65	Tensile, flexural, impact
R 40:60	Tensile, flexural, impact
30:70—(0, 90, 90, 0)	Tensile
30:70—(0, 45, −45, 0)	Tensile

The following ASTM standards are used as guides for the tests. The sample plates are cut into test specimens using a water jet cutter according to dimensions specified in the respective ASTM standards.

3.1.1. Tensile tests

Tensile tests are used to determine modulus and strength. Tensile strength at peak and yield loads has been investigated to evaluate its modulus of elasticity and percent elongation at break for samples of varying fiber content. For tensile tests, dog bone-shaped specimens are put in an instron load frame model 8511 universal testing machine and stretched until broken. Specimens featuring both randomly oriented and directionally aligned fibers are tested as specified in Table 2 with speed of extension at 10 mm/min. No extensometer is used because damage to the extensometer is likely to occur when the sample breaks. Instead, crosshead displacement is used for displacement measurement, and the modulus has been calculated while adjusting for machine compliance. Five test specimens are cut and tested from each sample plate in order to enable determination of average result values.

Figure 1 shows average true stress-strain curves of five test specimens cut from sample plates for R 15:85, R 25:75, R 35:65, R 30:70—(0, 45, −45, 0) and 30:70—(0, 90, 90, 0). The tensile strength concerning the fiber ratio shows that beyond 30 wt%, the tensile strength decreases. It can be learnt that as the ratio of fiber increases, the interaction between the fibers inside the composite increases resulting in higher fiber contact that leads to poor interfacial bonding between the fiber and matrix. Because of this poor interfacial bonding, effective load transfer does not take place and leads to early failure of samples.

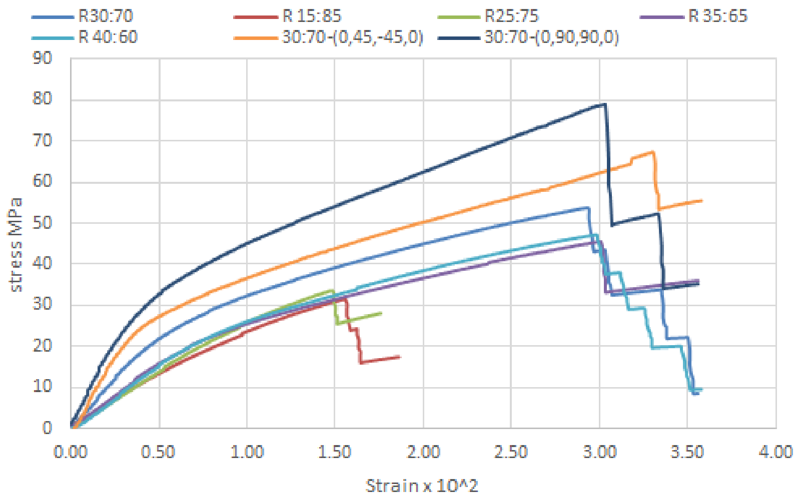

Figure 1. Average stress-strain curves, tensile loading case.

Average calculated peak tensile strength, modulus of elasticity and percent elongation at break for all samples are shown in Table 3. For test specimens with 30% fiber and 70% epoxy, the tensile strength of test specimens with oriented fibers is much higher than for those with randomly oriented fibers. The highest yield stress is obtained for specimens with (0, 90, 90, 0) degree fiber orientation.

The SEM (scanning electron microscope) images of the fracture surfaces are investigated using a TM3000 microscope, with speeding up the voltage of 15 kV, at various magnifications. The investigation mounted all specimens onto aluminum stubs and sputter-coated with platinum and palladium to make them conductive before observation. SEM images for one R 15:85 tensile specimen are shown in Figures 2 and 3, for morphological illustration of the composite surfaces at breakage. The figures show evidence of fiber fracture and pull-out along with resultant voids left in the matrix from fiber pull-out. The fiber pull-out occurs because of weak bonding between the natural fibers and the epoxy Matrix, which is the main disadvantage of natural fiber-reinforced composites.

Table 3. Average tensile properties of tested specimens.

Sample	Average modulus (GPa)	Average peak strength (MPa)	Average yield stress (MPa)	Average elongation (%)
R 15:85	1.95	35.6	33.5	2.85
R 25:75	2.35	40.4	38.8	2.77
R 30:70	2.53	58.0	56.6	6.32
R 35:65	2.49	54.6	50.4	5.64
R 40:60	2.39	50.1	49.1	4.85
30:70—(0, 45, −45, 0)	3.87	73.8	67.4	8.84
30:70—(0, 90, 90, 0)	4.43	85.5	80.7	7.78

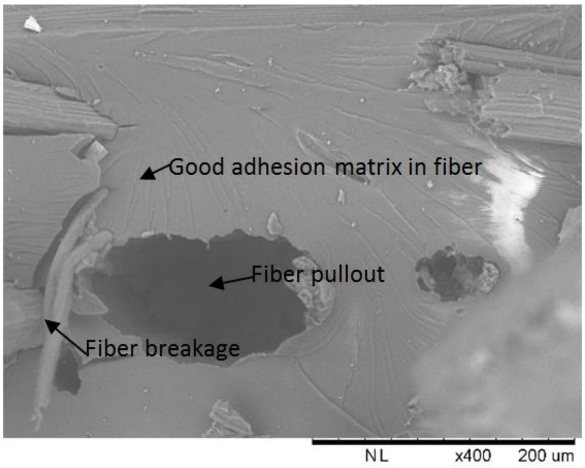

Figure 2. SEM micrograph of tensile fractured surface of R 15:85 random composite at magnification 400×.

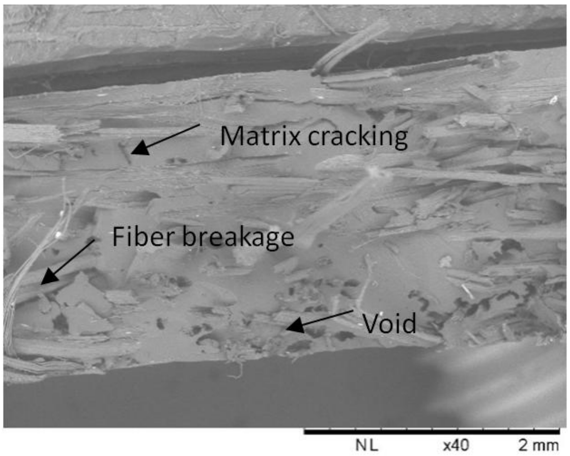

Figure 3. SEM micrograph of tensile fractured surface of R 15:85 random composite at magnification 40×.

3.1.2. Flexural tests

Flexural tests are performed using an instron load frame model 8511 universal testing machine according to the [18] ASTM D 7264/7264 M-07 standard test methods. Flexural tests are used to determine flexural stress at peak load, strain at peak load, and chord modulus. Procedure A is followed where the specimen is held by two cylindrical support noses while a third cylindrical loading nose applies a force to the center of the specimen, causing it to bend. Specimens are tested using a 32:1 span to thickness ratio and a support span of (50.8 mm) is used for all specimens.

The loading nose is lowered midway between the two support noses at a rate of 2 mm/min. After the peak load is reached, the load needed to bend the specimen is reduced. Break sensitivity on the machine is set for 75%, which stops the test when the load decreases to 25% of the peak load value.

In Table 4, average values for flexural stress and strain at peak load, as well as chord modulus, are shown. The following procedures are used to find stress, strain, and chord modulus :

$$Maximum\ Flexural\ Stress\ =\frac{3PL}{2bh^2} \tag{1}$$

where P is the peak load, L is the distance between loading noses, b is test specimen width and h is thickness in the Eq 1.

$$Maximum\ Strain\ =\frac{6hx}{L^2} \tag{2}$$

where h is test specimen thickness, and x is the maximum specimen deflection in the Eq 2.

Chord modulus is found by dividing the change in stress over a strain range of 0.002. SEM images are taken at the locations of specimen failure.

Peak flexural strength; cord modulus and Maximum strain of sisal reinforced epoxy composite are shown in Table 4 which is calculated as per the standard and given equation 1 and 2. Both the cord modulus and flexural strength are found to increase with increasing fiber content up to 30 wt%, where strong fiber-matrix adhesion is obtained. The superior results of the composites with 30 wt% fiber is also seen in Figure 4. Failure due to flexural loading for all tests occurs due to tension at the loading nose, causing fiber fracture and matrix cracking (Figure 5).

Table 4. Flexural test results.

Smple type	Max peak load (Kg)	Max flexural stress (MPa)	Max strain	Δ Strain (Δl/l) (mm/mm)	Δ Stress	Chord modulus (GPa)
R 5:85	3.67	66.63	0.0705	0.00200	6.69	3.35
R 5:75	13.41	75.85	0.0378	0.00233	8.54	3.62
R 30:70	26.41	84.79	0.0532	0.00198	7.20	3.64
R 35:65	25.88	76.62	0.0529	0.00199	6.16	3.1
R 40:60	26.21	82.52	0.0613	0.00199	6.44	3.23

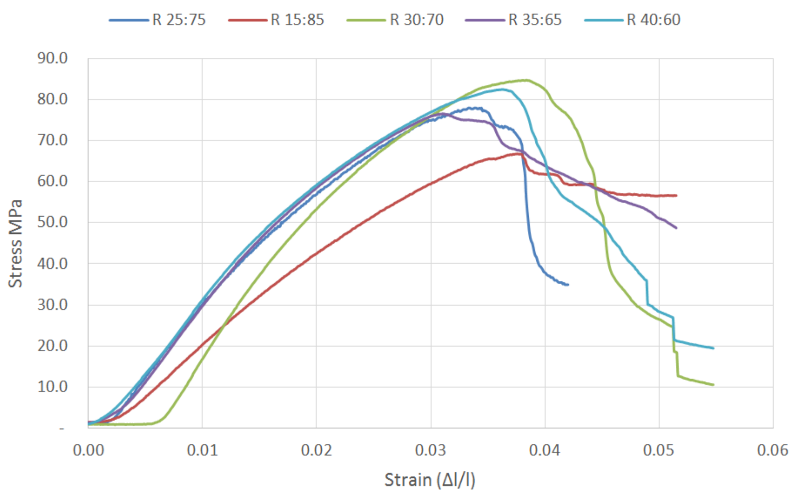

Figure 4. Average stress strain curves for flexural loading.

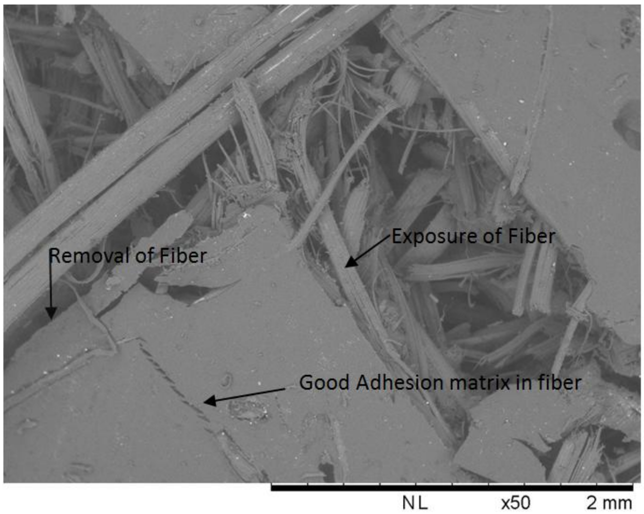

Figure 5. SEM micrograph of fractured surface of R 30:70 composite after flexural test with 50× magnification.

3.1.3. Impact test

Specimens are prepared for the Izod impact test according to [20] ASTM D256, ISO 180, using test method A with a pendulum capacity of 2.74 J. he impact properties of the composites are studied by applying an indentation load normal to the specimen's longitudinal axis. A notched specimen is secured with the notch facing the approaching pendulum. The pendulum breaks the specimen are the height of the pendulum swing is corrected for wind resistance. Specimen breaking energy is calculated automatically by the impact test machine.

Table 5 shows the impact strength and impact energy of sisal reinforced epoxy composites. Impact properties are found to increase with increasing percentage of sisal fiber content up to 40 wt%. As can be seen in the SEM picture in Figure 6, crack formation in the matrix and broken fibers are associated with the impact damage.

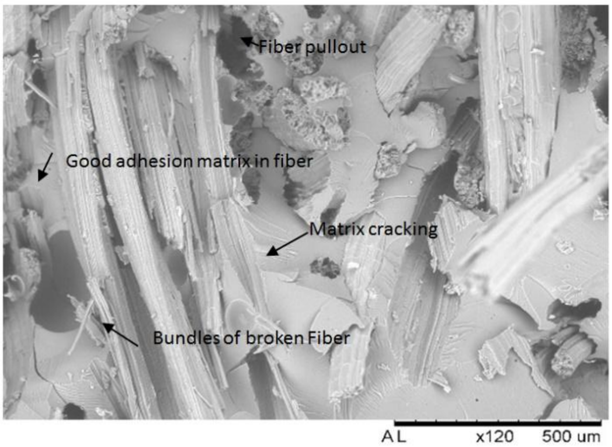

Figure 6. SEM micrograph of fractured surface of R 15:85 composite after impact test at magnification 120×.

Table 5. Impact property of sisal reinforced epoxy composites.

Sample type	Impact energy (J)	Average impact strength (kJ/m^2)
R 15:85	0.21	9.35
R 25:75	0.36	11.89
R 30:70	0.60	13.28
R 35:65	0.71	16.39
R 40:60	1.11	24.49

Table6. Comparison of mechanical properties reported in this work with literatures.

Fiber	Matrix	Fiber orientation	Ratio fiber /matrix	Method of fabrication	Type of treatment	Tensile strength (MPa)	Tensile modulus (GPa)	Impact srength (kJ/m^2)	Flexural strength (MPa)	Flexural modulus (GPa)	Reference
Sisal	Epoxy	Random	30/70	Hand layup	NaOH 10%	58	2.53	13.28	84.79	3.62	Current work
Sisal	Epoxy	0,90,90,0	30/70	Hand layup	NaOH 10%	85.5	4.43	-	-	-	Current work
Sisal	Polyester	Random	30/70	Hand layup	NaOH 18%	65.93	1.85	-	115.62	4.83	[21]
Sisal	Epoxy	Random	30/70	Hand layup	NaOH 10%	83.96	1.58	22.03	252.39	11.32	[22]
Sisal	Polypropylene	Short	30/70	Hand layup	Alkaline	34.4	0.94	-	-	-	[23]
Sisal	Polyester	Long	30/70	Hand lyup	Alkaline	44.4	1.04	-	-	-	[24]
Sisal	Epoxy	Mat form	30/70	Hand lyup	-	89.3	0.39	-	-	-	[24]
Sisal	Epoxy	Long	39.6/60.4	RTM	-	36.1	2.19	-	74.5	3.07	[25]
Hemp	Polypropylene	Random	50/50	Hand layup	Alkaline	50	6.5	53	85	4	[27]
Jute	Epoxy	Random	30/70	Hand Layup	Alkaline	69.5	6.28	-	89.63	5.94	[26]

3.2. Comparison results with other researchers

Table 6 shows measured mechanical properties of fiber-reinforced composites determined in various laboratories. Although some researches featured sisal fibers as the reinforcing agent, the properties of sample plates can vary widely depending on the geographic area of sisal cultivation and method of manufacture. Mechanical properties vary for specimens characterized in various laboratories but are not inconsistent with each other. Our results featuring 30 wt% sisal fiber reinforced composites, represent materials and a manufacturing method that are viable for Ethiopia.

4. Conclusions

The experimental investigation on mechanical properties of sisal fiber-reinforced composites leads to the following conclusions.

We make sisal fiber-reinforced composites with various fiber orientation patterns and fiber-to-epoxy weight ratios. A hand layup compression molding method with the cold-press process is used for manufacturing the specimens which provide us an opportunity of replacing existing synthetic fiber-reinforced materials with higher strength, low-cost and environmentally friendly alternative.

The maximum tensile strength and modulus are 85.5 MPa and 4.5 GPa respectively, observed for specimens with 30 wt% fiber in a (0, 90, 90, 0) pattern. The maximum flexural strength and chord modulus are 87.1 MPa and 3.6 GPa respectively which are observed in specimens with random fiber orientation and 30 wt% fiber. The maximum impact strength is 24.5 kJ/m^2, correspond to specimens with random fiber orientation and 40 wt% fiber content. For all tests, evidence of fiber pullout, matrix cracks, and fiber fracture are observed. From the results, composite materials with 30 wt% fiber content have the best overall mechanical properties.

The tensile strength and flexural strength of sisal reinforced epoxy composites are greatly influenced with the ratio of the fiber and matrix and it exhibits a decrease of its property when the fiber content is beyond 30 wt% of fiber the impact strength increases with the increase of sisal fiber ratio, therefore, it needs further study to find the optimum ratio of sisal fiber to matrix to define the best material combination for impact case.

It is possible to use sisal reinforced epoxy composites as a substitute material for automotive parts, such as door panels, seat backs, bolsters, load floors, and packaging trays. The raw materials and manufacturing method represent a viable route for the production of such composites in Ethiopia.

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Conflict of interests

The authors declare no conflict of interest.

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