Fracture toughness analysis of woven sisal-glass fibers hybrid composite

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Abstract. The purpose of this experimental work was to study the mode I fracture toughness behavior of woven sisal and E-glass fibers hybrid composite material under mode I loading conditions in order to measure the resistance of the material to fracture behavior. The sisal fibers were extracted from the sisal plant manually. 5% NaOH was used for the sisal fiber surface treatment. Then the woven sisal fiber was prepared from treated fibers by hand weaving. Compact Tension specimens were prepared according to the ASTM D5045-99 standard and the hand lay-up technique. The result showed that the mode I fracture toughness value of a specimen of 5mm thickness has (K_{IC}) of 18.34 MPa. √m fracture toughness value under mode I loading conditions. It is a useful parameter used for designing and setting preconditions for engineering applications by measuring the resistance of a material to fracture under mode I loading conditions, which are used in diverse engineering applications. Fracture toughness test results showed the manufactured hybrid specimens' performance and applications for the different engineering materials for construction purposes (such as partitions in construction, tables, and ceilings), for light-weight vehicle parts (such as boards), and for the replacement of synthetic materials with natural fibers in engineering applications.

1. Introduction

Nowadays, the application of hybrid composite materials has recently increased in the fields of aerospace, automobile, nuclear, marine, biomedical, and other engineering areas due to the following reasons: high strength or stiffness for lower weight, superior fatigue characteristics, the facility to change fiber orientations, etc. [1]. Natural fibers and synthetic fibers are used for the reinforcement in the hybrid composites [2,3]. Even though synthetic and natural fibers have their own advantages and play a great role as reinforcements in hybrid composites, both synthetic and natural fibers also have their own drawbacks, like recycling, reusability, and biodegradability problems for synthetic fibers, as well as high moisture absorption and poor mechanical properties for natural fibers [4]. The hybridization of natural fibers with synthetic fibers improves performance and minimizes the drawbacks that come from both natural fibers and synthetic fibers by taking advantage of both natural and synthetic fibers [5].

At the same time, hybrid composite materials are exposed to different problems such as inter-ply cracking, voids, discontinuities, and fiber cracking. Among these three problems, mode I fracture toughness is a common failure mode in hybrid composite materials. The fracture mechanism is very complicated, and many factors will influence the failure process [6]. The uses and advantages of hybrid composite materials over metals were found to be preeminent and the best alternative [7]. As mentioned, due to the many advantages, most researchers have recently focused on the fracture toughness of hybrid composite materials.

Fracture toughness is very important mechanical property since the occurrence of flaws is not completely avoidable in the processing, fabrication, or service of a material/component. So, it measures the resistance of a material to fracture that is used in diverse engineering designs including mechanical, civil, materials, electronics and chemical engineering applications. If a material has high fracture toughness, it is more prone to ductile fracture. Brittle fracture is characteristic of materials with less fracture toughness [8].

In this paper, compact tension specimens are prepared for a fracture toughness test. The estimation of crack length after the initial crack has been generated through software integrated with universal testing machines during the test. The test has been developed on the universal testing machines according to the guidelines of ASTM standards, and results were obtained accordingly.

2. Materials and Method

Materials that are utilized directly for the manufacturing of the sisal and glass fiber hybrid composite sample are woven sisal fiber, E-glass fiber, sodium hydroxide, polyester resin with its hardener, a press machine, and a universal testing machine. The basic materials used to manufacture composite material are listed in figure 1 below.

Figure 1. Basic materials.

2.1. Sisal and extraction process of sisal fibers

From the Ethiopian rift valley, sisal plant leaves were collected after cutting at their base from harvest. The leaves were trimmed in a longitudinal direction into strips. The Fibers extraction was done manually, and the extracted Fibers will be washed with pure water to remove dust from the Fibers and then dried with sunlight [9]. Figure 2 Shows the extraction process of sisal fibres.

Figure 2. Extraction of sisal Fibers.

2.2. Sodium hydroxide treatment of sisal fiber

The methods for surface modification can be done by physical or chemical treatment according to the way they modify the Fiber surface [10]. Chemical treatment of natural Fibers is used to remove waxy substances, pectin, lignin, and natural oils from the external surface of the Fiber cell wall in order to improve the surface adhesion properties for the Fiber-matrix interface, the Fiber's shear strength, rigidity and stiffness, moisture absorption problems, and roughness of the Fiber. Ionization of the hydroxy group is done by adding aqueous sodium hydroxide to natural Fiber. Sodium hydroxide is the most commonly used chemical for bleaching and cleaning the surface of plant Fibers [11]. However, when the percentage of sodium hydroxide increases, the Fibers' properties are affected, reducing their bonding capacity during the preparation of the composites. The chemical reaction that takes place between sisal Fiber and an aqueous sodium hydroxide solution.

$$\text{Sisal Fiber - OH} + \text{NaOH} \rightarrow \text{Fiber-O-Na} + H_2O \quad (1)$$

Based on several kinds of literature and a good result from my trial work [i.e., by mixing 1 Liter of distilled water with a medium percentage of sodium hydroxide (i.e., 100 g), 400 g of NaOH pellet was mixed with 4 Liters of distilled water at ambient temperature and soaked for 3 hours for this work. Then the soaked Fibers were washed with pure water to get a neutral pH value. The soaked Fibers were washed several times with normal water to purify them from excess NaOH and to get a neutral Ph value, and lastly, the Fibers were allowed to dry in the sunlight for 24 hours. Since NaOH can react with air, which increases the water content (moisture) in the solution, the solution of Fibers and NaOH must be kept under a vacuum. Due to this, as shown in Figure 3 (b), the container was covered with a plastic sheet in order to create a vacuum inside the bath. Figure 3 shows the flow chart of alkali treatment for sisal Fiber.

Figure 3. Alkali treatment of sisal Fibers.

2.3. Woven sisal fiber preparation

Zhang and Kelkar AD stated that the woven fabric textile structures are better than others that are used as reinforcement in composites due to their good mechanical characteristics, conformability, and design possibilities with different orientations. The composite laminates formed from woven fabrics have good properties in mutually orthogonal directions as well as more balanced properties and better impact resistance than the unidirectional laminates. [8,11]. Therefore, after the Fibers dried, the woven fabric of treated sisal Fibers having weft and warp in the perpendicular direction (00/900) was prepared as bi-directional layers. The dimensions of the woven fabric sample were 38 cm in width and 38 cm in length as shown in figure 4 below.

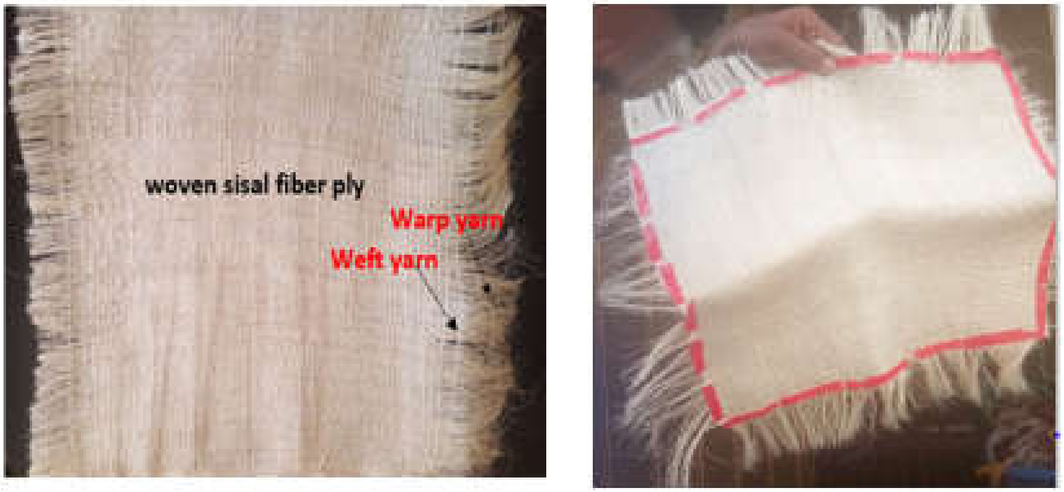


Figure 4. Manufactured woven sisal Fiber ply.

2.4. Glass fiber

Common E-glass fiber types of fiberglass are found in composite materials and have good combinations of chemical resistance, mechanical, and insulating properties. Comparing with other types of glass fibers, E-glass fiber has high resistance to chemical agents, good electrical insulator characteristics, higher strength and impact resistance, low thermal conductivity, low susceptibility to moisture, and dimensional stability at high temperatures [3]. However, they also have their own disadvantages, such as low stiffness, a short fatigue life, and being highly sensitive to temperature [4]. Due to the mentioned characteristic, E-glass fiber has been used as sisal fiber reinforcement for this work. Randomly oriented E-glass fiber was procured from World Fiber Glass and Water proofing Engineering plc, located in Addis Ababa. Figure 5 shows used randomly oriented glass fibers.

Figure 5. Randomly oriented glass fibers.

Here, fibers are made of fiber glass and sisal fibers. In this study, primary data (fiber density and matrix densities) about E-glass, sisal fiber, and polyester resin are taken from literature reviews. The calculated results are obtained from primary data using the rule of mixtures formula, and the values are evaluated and presented in Table 1.

Table 1. Fibers and matrix volume values.

Primary data		Calculated results	
Parameters	Value	Parameters	Value
Sisal fiber ply weight (Wf-sisal)	71.25 g	Sisal fiber volume (Vf- sisal)	53.6 cm^3
Glass fiber ply weight (Wf-glass)	171.05 g	Glass fiber volume (Vf- glass)	66.6 cm^3
Total fiber weight	242.3 g	Total fiber volume –	120.2 cm^3
Sisal fiber density (ρf-sisal)	1.33 g/cm^3	Matrix volume (Vm)	121.5 cm^3
Glass fiber density (ρf -glass)	2.57 g/cm^3	Total fiber volume ratio (VF)	50 %
Matrix weight (Wm)	145.8 g	Matrix volume ratio (VM)	50 %
Matrix density (ρm)	1.2 g/cm^3	Total fiber weight ratio (WF)	62.4 %
		Matrix weight ratio (WM)	37.6 %
Ply thickness		Woven sisal fibers ply thickness	0.35 mm
		Randomly oriented E-glass fibers ply thickness	0.25m

2.5. Hand lay-up techniques

Hand lay-up fabrication techniques were adapted to fill up the prepared mold with an appropriate amount of polyester resin mixture, glass fiber ply, and woven sisal fiber ply, starting and ending with layers of resin. The quantity of catalyst added to resin at room temperature for curing was 1% of the volume of resin. The advantages of hand lay-up techniques are low capital investment, simplicity, and versatility. However, it is mostly labor-intensive [4,12]. Mold release is essential for preventing the matrix from sticking to the mold when the composite is separated. The most common type of release agent used for this thesis work is paste wax (oil). A better surface finish is obtained with the use of paste wax. Usually, paste wax is quick, cheap, and widely available and figure 6 shows hand lay-up method that used for this manufacturing process.

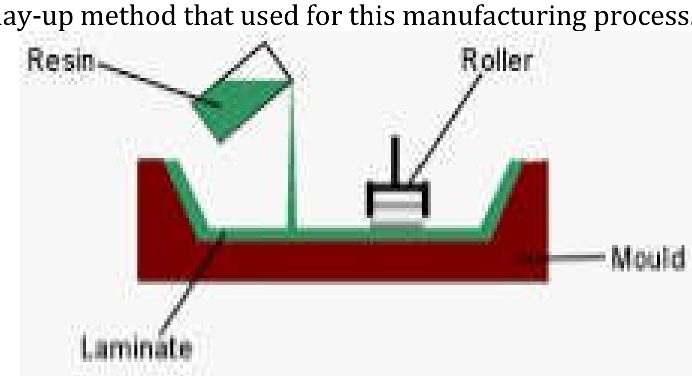


Figure 6. Hand lay-up method.

2.6. Hybrid composite plies and laminates

Based on the reinforcement, matrix, and curing process, the component architecture of the bidirectional woven sisal and E-glass-reinforced polyester hybrid composite has been defined as glass-sisal-sisal-sisal-glass. Ten plies of woven sisal fibers are fabricated, and two plies of randomly oriented E-glass fibers are prepared for a 5mm-thick hybrid specimen hybrid plies configuration as shown in figure 7 below.

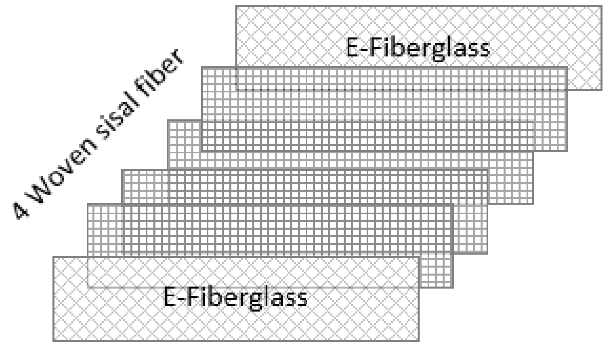


Figure 7. Hybrid plies configuration.

2.7. Fabrication process of a hybrid specimen

As specimen fabrication flow shown in figure 8 below, Polyester resin is mixed with a hardener to prepare the composite plate, and the woven sisal fiber ply and glass fiber ply have been arranged on the mold surface according to their specific stacking sequences. Then, the first fiber ply is laid. This layer is wetted with resin and then softly pressed using a roller to make the resin that was added in. At last, press the mold on the hydraulic press machine with a compression pressure of 100 bar (10 MPa) and leave it for 12 hours at room temperature for consolidation.

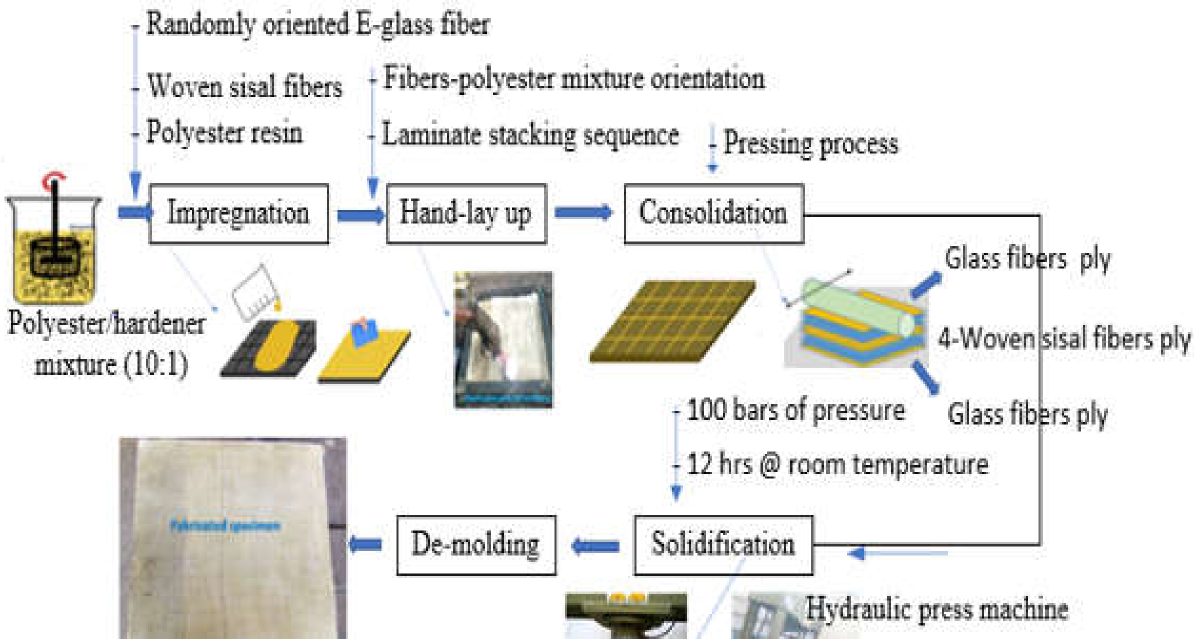


Figure 8. Specimen fabrication flow chart.

3. Experimental setup and testing conditions

3.1. Band saw, ASTM standards for dimensions

The prepared hybrid composite specimen was cut using a band saw into the desired dimension based on the respective standards for compact tension testing and moisture absorption that have been performed using a universal testing machine. American Society of Testing Materials standards ASTM D5045-99 were followed while preparing the compact tension specimen of the rectangular test specimen, and sample dimensions and configurations are shown in Figure 9.

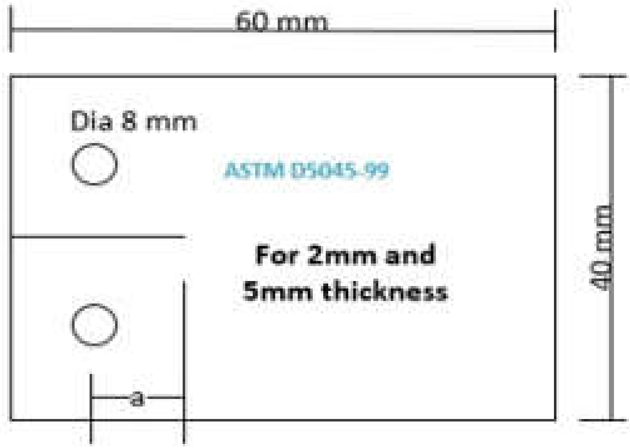


Figure 9. 2D and 3D specimen's dimension and configuration as per ASTM D5045-99.

3.2. Universal testing machine

Compact tension fracture toughness tests were studied using a universal testing machine of model WP 310 which has a test load capacity of up to 50 KN with a maximum piston stroke of 150 mm and crosshead speed of 6 mm/sec at Bishoftu Defense College of Engineering. The data acquisition software is used to acquire data from the machine during testing. For all the specimens, the load is applied continuously from the dynamometer load cell until the specimen fails during the test. figure 10 below is captured photograph of universal testing machine found at Bishoftu Defense College of Engineering.

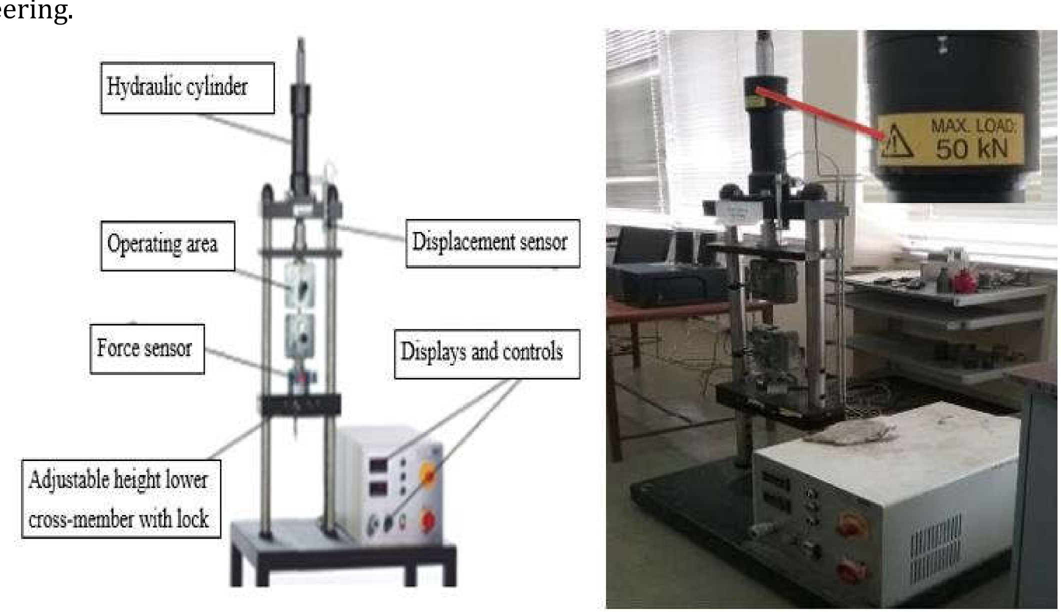


Figure 10. Universal testing machine.

3.3. Mode-I fracture toughness test using compact tension (ASTM D5045-99)

A specimen of compact tension was prepared for a 0.5 ratio value between crack length, 'a', and crack width, 'w' (a/w = 0.5). All dimensions are as per the ASTM D5045-99 standard, and crack thickness (crack opening) is the thickness of the band saw blade. For each test, five compact tension specimens were prepared and tested using a universal testing machine with a cross-head speed of 6 mm/sec at room temperature. load and load line displacement were recorded from the given test, and the critical stress intensity factor was calculated for the recorded loads. The typical prepared 5mm compact tension test specimens are shown in Figure 11.

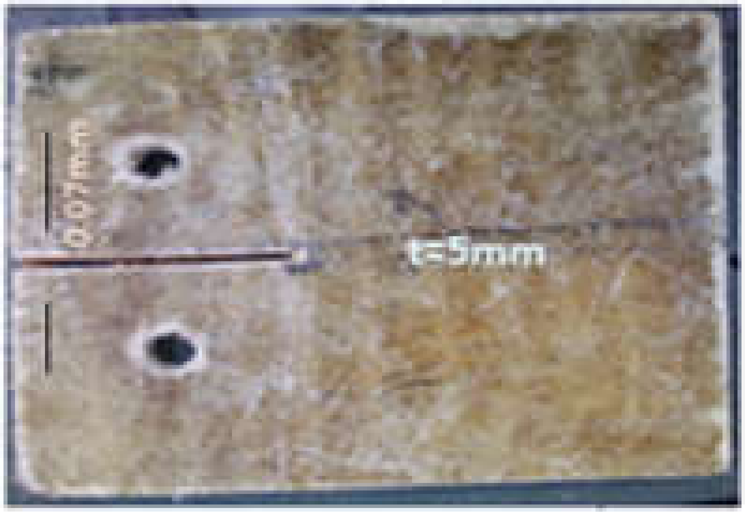


Figure 11. Manufactured compact tension specimen.

4. Result and Discussion

4.1. Mode-I fracture toughness tests results

Five test samples were prepared from woven sisal and E-glass fiber hybrid composites for the compact tension test. Experimental results of these specific tests have been summarized using graphs, which can relate different material properties that are used in fracture mechanics to show the fracture resistance of a given composite material. In this experimental work, loading and load advancement, crack length, and crack advancement were recorded automatically from software that was integrated with the universal testing machine. Figure 12 shows fracture toughness test result of tested specimens.

Figure 12. Tested specimens result of 5mm thickness.

4.2. Stress intensity factor and strain energy release rate

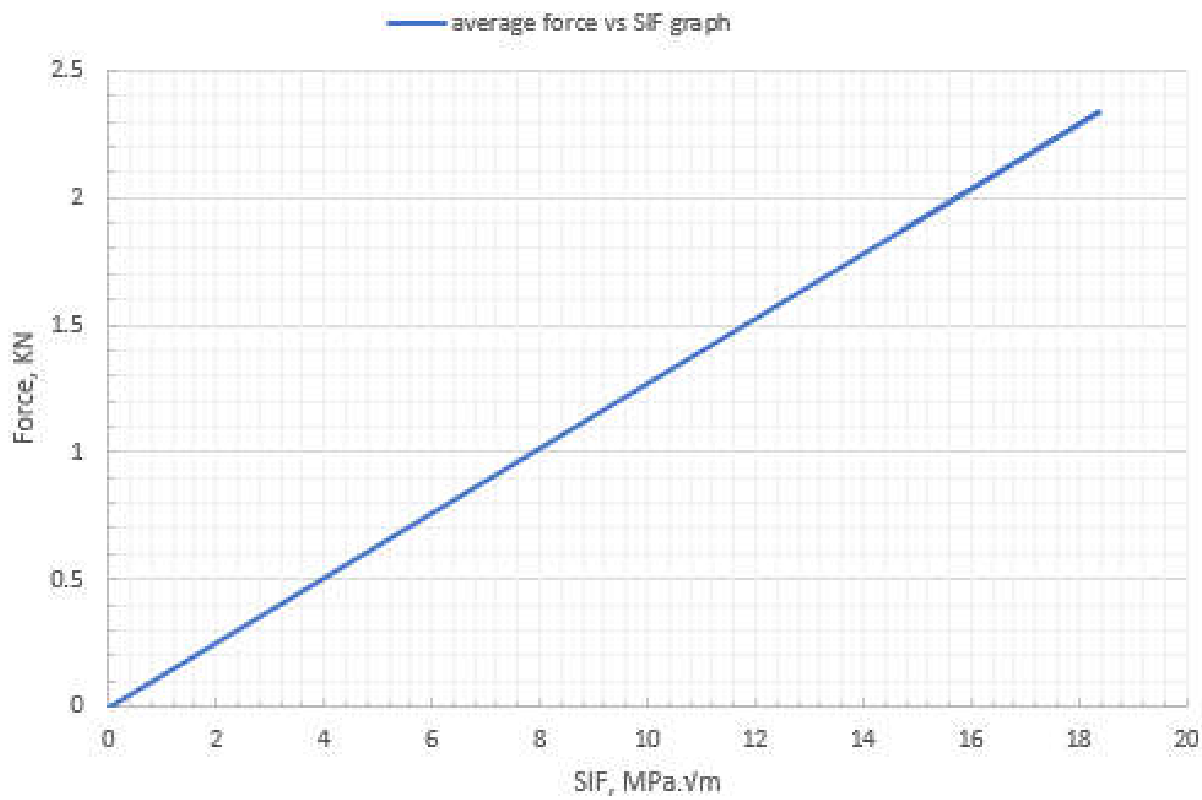
The stress intensity factor of the compact tension specimen was computed according to ASTM D5045-99 [12]. Crack and load advancement generated by software and K_{IC} or S_{IF} calculated as per ASTM D5045-99 standard.

$$KIC = \frac{P}{h/w}\left(f\left(\frac{a}{w}\right)\right) \quad (2)$$

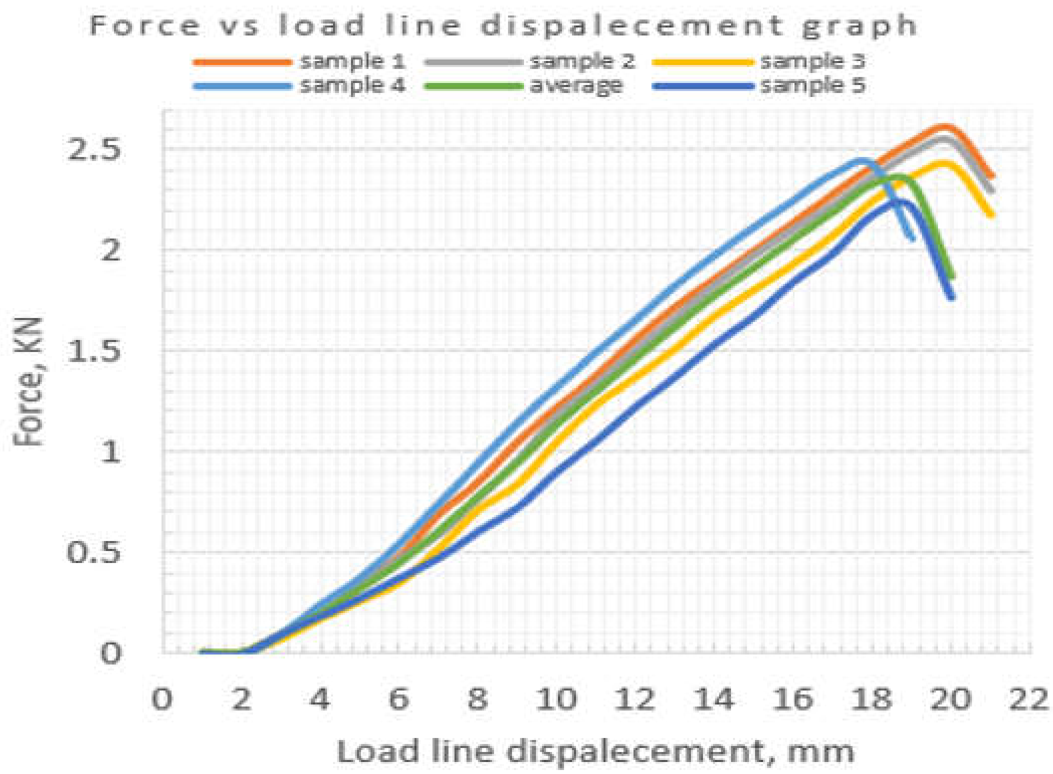
Where: K_{IC} is critical stress intensity factor, p is applied load, h and w are hybrid specimen thickness and width, respectively, and f(a/w=0.5) is geometry factor taken from standard. The critical strain energy release rates were also computed with the compliance calibration method, which employs the concept of compliance as the ratio of deformation to applied load.

The results of fracture toughness tests are shown in the following graphs:

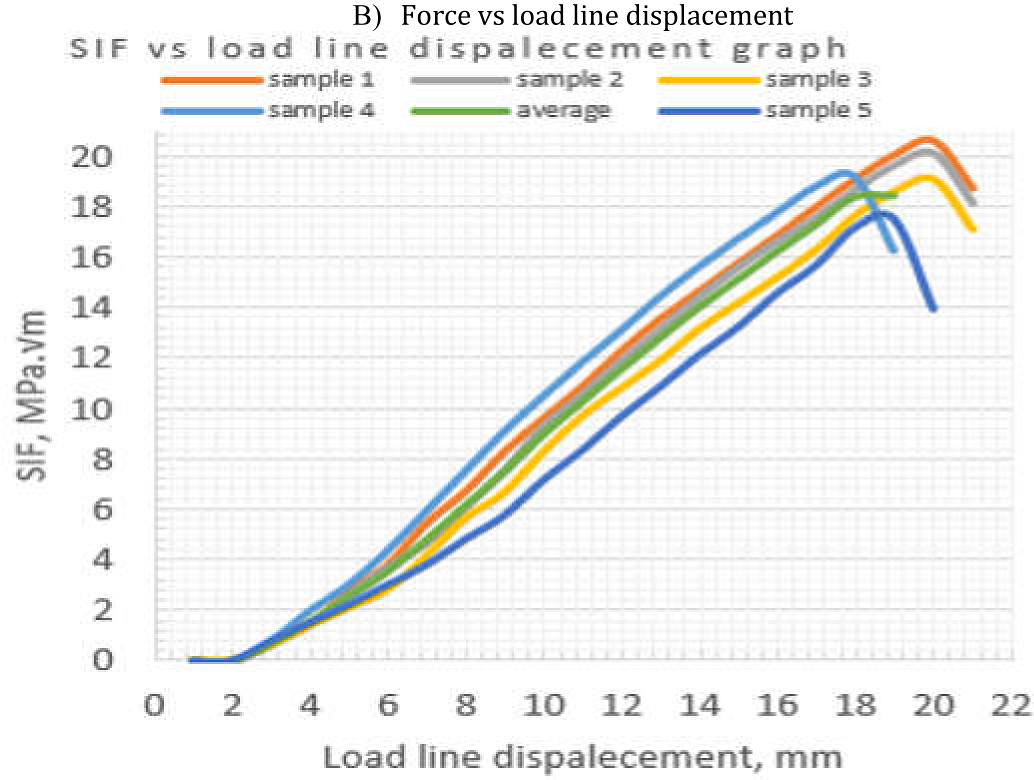
1. Compact tension specimens



A) Force vs stress intensity factor



B) Force vs load line displacement



C) Stress intensity factor vs load line displacement

Figure 13. Compact tension test results.

SGHC-compact tension of 5 mm thick rectangular specimen was subjected to 2.328 KN. The crack extension is 11.55 mm. As observed from the experimental result, the average critical stress intensity factor and the critical strain energy release rate of specimens is summarized in table 2.

Table 2. Fracture toughness result.

Fracture toughness			
K_{IC}	Standard deviation	$G_{IC\ (KJ/m^2)}$	Standard deviation
18.34	1.301	13.57	1.485

According to the Z. Salleh experimental work on mode I fracture toughness of kenaf-woven glass fibers and investigated a result of 252.1 MPa. √mm (13). Prem Kumar studied the fracture toughness of short banana fiber composites and investigated a fracture toughness value of 2.911 MPa (9). As shown from the results and compared with above mentioned authors work, the manufactured woven sisal-glass fiber hybrid composite is a tough material and is used for the replacement of some specific materials.

5. Conclusion

Hybridization of natural fibers with synthetic fibers is very essential in order to improve the mechanical and physical properties of natural and synthetic fibers. Fracture toughness is a very important mechanical property since the occurrence of flaws is not completely avoidable in the processing, fabrication, or service of a material or component. So, it measures the resistance of a material to fracture that is used in diverse engineering designs, including mechanical, civil, materials, electronics, and chemical engineering applications.

Therefore, this paper intends to study the mode I fracture toughness behavior of woven sisal and E-glass fiber hybrid composites experimentally. The results of the experimental work showed that the mode I fracture toughness value of a rectangular 5mm thick specimen is K_{IC} =18.34 MPa. √m. From all the results and comparisons, the fabricated hybrid composite specimen has a good fracture toughness that shows the performance and applications of the materials in diverse engineering applications, and the manufactured hybrid composite is a tough material and is used for the replacement of some specific materials.

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