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Research article

Experimental investigation of fracture toughness for treated sisal epoxy composite

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Abstract: The aim of this work is to show the fracture toughness behavior of sisal reinforced epoxy composite using fracture toughness testing method by including most important fracture mechanics parameters which is called stress intensity factor K.

The fracture toughness tests of chopped sisal fiber reinforced epoxy composite materials were carried out using test samples which were prepared according to the ASTM standard. The samples have been fabricated by using the epoxy resin (AY-105) as a matrix and the hardener (HY-951) and the chopped sisal fiber as a reinforcement material with the 15%, 25%, 30%, 35% and 40% fiber weight fraction, random oriented chopped fibers by using hand layup fabrication technique.

The experimental results justify that the 30/70 composition of fiber and matrix has superior fracture characteristics with K_{IC} of 5.54 MPa m$^{1/2}$ and critical strain energy release rate (G_{IC}) of 13.72 MPa mm and results of this study indicate that using chopped sisal fibers as reinforcement in polymer matrix could successfully develop a composite material in terms of high strength and rigidity for light weight material.

Keywords: sisal fiber; epoxy composite; hand layup; stress intensity factor (K_{IC}); strain energy release rate (G_{IC})

1. Introduction

A composite material in its essence is a combination of two or more different materials that are mechanically bonded together. Each of the various components retains its identity in the composite and maintains its characteristic structure and properties. Generally, the structure of a composite consists of two phases, matrix and reinforcement. The matrix is a continuous phase and the reinforcement is a discontinuous one. The duty of reinforcements is attaining strength of the composite and the matrix has the responsibility of bonding of the reinforcements. There are recognizable interfaces between the materials of matrix and reinforcements. The composite materials, however, generally possess combination of properties such as stiffness, strength, weight, high temperature performance, corrosion resistance, hardness and conductivity which are not possible with the individual components. Indeed, composites are produced when two or more materials or phases are used together to give a combination of properties that cannot be achieved otherwise [1,2].

Moreover, the matrix used to protect the fibers from environmental damage before, during and after composite processing. In order to exhibit better strength for the new developed composite material, proper design is highly required. Composites have a lot of application areas in different disciplines, such as in mechanical, electrical, thermal, tribological, and environmental applications. Composites are multifunctional material systems that afford characteristics not obtainable from any distinct material. They are cohesive structures made by physically combining two or more compatible materials, special in composition and characteristics and sometimes in form [3].

The following are the basic reasons why composites are selected for certain applications:

- High strength to weight ratio (low density high tensile strength);
- High crawl or creep resistance;
- High tensile strength at lofty temperatures;
- High toughness.

Most commonly polymers are used as a matrix. Overall the mechanical properties of polymers are insufficient for many structural applications. Particularly their strength and stiffness are near to the ground compared to metals and ceramics. These difficulties are surmounted by reinforcing polymers with other materials. Secondly the processing of polymer matrix composites doesn’t require high pressure and high temperature, and equipment required for manufacturing polymer matrix composites are simpler. For this reason, polymer matrix composites developed quickly and almost immediately became trendy for structural applications.

Nowadays, polymer composite with natural fibers are mainly used for different engineering application, predominantly for the development of the interior panel of automobiles. Common fibers reinforced composites are composed of fibers and a matrix. Fibers are the reinforcement and the main source of strength whereas matrix glues all the fibers together in shape and transfers stresses between the reinforcing fibers. Sometimes, filler might be added to smooth the manufacturing process, impact special properties to the composites, and/or decrease the product cost [4].

Natural fibers reinforced polymer composites highly fascinated designers by their several advantages such as low weight, low cost, high availability, easy productivity, their friendly to environment and high specific mechanical performance. Natural fibers have advanced mechanical properties like stiffness, flexibility and modulus compared with glass fibers [5]. Their availability, renewability, low density, and price as well as acceptable mechanical properties make natural fibers more attractive ecological alternative than glass, carbon and man-made fibers used for the manufacturing of composites. The natural fiber contained composites are more environmental friendly, and are used in transportation (automobiles, railway coaches, aerospace), military applications, building and construction industries (ceiling paneling, partition boards), packaging, consumer products, etc.

The interaction between fiber and matrix play a humongous role to affect mechanical properties of the composite material. On the other side, there are some limitations with natural fibers such as their poor mechanical properties and high moisture absorption [6].

The natural fiber composites can be very cost effective for following applications:

- Building and construction industry: panels for partition and false ceiling, partition boards, wall, floor, window and door frames, roof tiles, mobile or pre-fabricated buildings which can be used in times of natural calamities such as floods, cyclones, earthquakes, etc.;
- Furniture: chair, table, shower, bath units, etc.;
- Electric devices: electrical appliances, pipes, etc.;
- Everyday applications: lampshades, suitcases, helmets, etc.;
- Transportation: automobile and railway coach interior, boat, etc.

Fracture toughness is frequently used as a standard term to measure material resistance to extension of a crack. The experimental measurement and standardization of fracture toughness play an imperative role in application of fracture mechanics methods to structural integrity assessment, damage tolerance design, fitness-for-service evaluation and residual strength analysis for different engineering components and structures [7]. Prasad et al. [6] studied that fracture mechanics is divided into two theories which are linear elastic fracture mechanics for brittle material and elastic plastic fracture mechanics for ductile material. Knott et al. [8] introduced a concept in 1973. A crack tip locates in the material and it seems like a line running from one location of the component to another location [8]. The high stress is concentrated at the crack tip. That's why a crack tip analysis is useful for getting the stress field and displacement. To make the problem simpler these two variables are converted into one variable known as stress intensity factor (K_{IC}). The fracture toughness values may also serve as a basis in material characterization, performance evaluation, and quality assurance for typical engineering structures, including nuclear pressure vessels and piping, petrochemical vessels and tanks, oil and gas pipelines, and automotive, ship and aircraft structures [9].

In this paper, fracture behavior of chopped sisal fiber reinforced epoxy polymer matrix composite has been studied. The analysis is carried out using experiment.

2. Objective/problem statement

A report by FAOSTAT in 2013, Ethiopia stands 11th in the world by sisal production. A mere comparison with other sisal producing countries shows that Ethiopia has performed poorly in using sisal plants in reinforcing polymers to form composite materials.

Composite designers and engineers recognize delamination as a primary failure mode. Unfortunately, modeling and predicting this behavior are not easy, but determining fracture toughness of sisal fiber reinforced polymer composite is very important, because fracture toughness test tell us the material property for the energy requirement of crack to grow per unit area extension. In general, designers and engineers have the ability to implement a stress analysis and utilize this in parallel with experiment strength data. In the case of engineering composites, fracture toughness is not easily accounted for.

The goal of the current work is to study the fracture toughness analysis of chopped sisal fiber reinforced polymer matrix composite with different ratio of fiber/epoxy (2D analysis) using experimental method for Mode one fracture and improve performance of engineering composites in commercial applications.

3. Materials and method

3.1. Matrix—epoxy resin

For this work, epoxy resin AY-105 was used as a matrix, which is purchased from the local sources in Addis Ababa, Ethiopia, and epoxy resin is cured by adding hardener HY-951, which causes a chemical reaction without changing its own composition as well as property. Density and dynamic viscosity of epoxy resin are 1.108 g/cm^3 and 11.789 Pa s, respectively, and the matrix material was prepared by using epoxy and hardener in the ratio 10:1, as recommended [10].

3.2. Fiber—sisal fiber

The required amount of sisal plant leaves for this thesis work are collected from highland part of Ethiopia after cutting at their base from the harvest and the fibers are extracted from the given plant manually with the help of knife. Initially the leaves trimmed in longitudinal direction into strips for ease of fiber extraction. The peel is clamped between the wood plank and knife, and we should hand-pulled through in longitudinal direction gently, removing the resinous material as shown in the Figure 1. After extraction process, the extracted fiber washed with pure water in order to remove and separate unwanted dusts from the fiber and it has been dried with sun and eventually the required fine fibers are obtained. In this thesis work, investigations were performed to analyze the effect of fiber length on the crack propagation. Therefore, the given sisal fiber was cut into two different fiber length (2 mm and 10–15 mm), using a pair of scissors and finally the chopped fiber is obtained.

(a) (b) (c) (d)

Figure 1. (a) Harvesting the sisal plant, (b) extraction pocess, (c) the extracted fiber, (d) chopping sisal fiber.

3.3. Preparation of composite

Epoxy of AY-105 mixed with hardener HY-951 is used to prepare the composite plate. The recommended weight ratio for mixing epoxy and hardener is 10:1. The mixer is strewed with stirrer for about one minute continuously. Hand-lay-up method was adopted to fill up the prepared mold with an appropriate amount of epoxy resin mixture and layers of random (chopped) sisal fibers, such that starting and ending with layers of resin. Fiber deformation and movement should be minimized to yield good quality, random fiber composites. Therefore, at the time of curing, the compression pressure of 50 bar (5 MPa) was applied on the mold to press and keep good bonding between the fibers and resin. The processed wet composites were then pressed hard and the excess resin is removed and dried.

In this work, chopped (short) sisal fiber has been used with fiber length of range of 2–15 mm and composite material samples were prepared with five different fiber-matrix volume compositions. The sisal fiber reinforced epoxy resins use different fiber matrix ratio of 15/85, 25/75, 30/70, 35/65 and 40/60 respectively for composites with chopped sisal fiber.

The pattern is made up of sheet metal with 300 mm × 250 mm × 20 mm and it contains the basic parts, such as base plate, cover frame and mold releaser as shown in Figure 2. The base plate is very thin plate which is placed inside the inning. The lid and base plate surfaces of the mold and the walls are coated with remover and allowed to dry. The functions of lid and base plates are to cover, compress the fiber after the epoxy is applied, and also to avoid the debris from entering into the composite parts during curing.

(a) (b)

Figure 2. (a) Mold plate, (b) mold plate with cover frame.

Mold release is essential for preventing the epoxy from sticking to the mold when the composites are apart. Even though, there are several types of mold release used depending on the mold material and desired characteristics of the finished part, the most common type and used for this thesis work is paste wax (oil), and polyethylene plastic for better surface finish of the composite.

The mold surface has been covered by polyethylene plastic laid and overall mold surface was painted with mold releaser (oil), then some mixture of epoxy resin poured on the prepared mold surface and chopped sisal have been arranged on this surface according to each specific fiber/matrix ratio, as shown in the Figure 3. We press the mold on press machine for consolidation and this sample is then left for 3–5 hours. The composite gets dried up within 3–5 hours in which the sisal fiber and the polymers adheres itself tightly in the presence of hardener. After the specified time, we put out the mold from the press machine. Then the mold steel lower attachment (plate) is slowly and gently hammered on the boundary of its attachment when the top (lid) and the composite separate out. Then plastics are removed from the steel mold carefully. Eventually, the required composites are produced as shown in Figure 4.

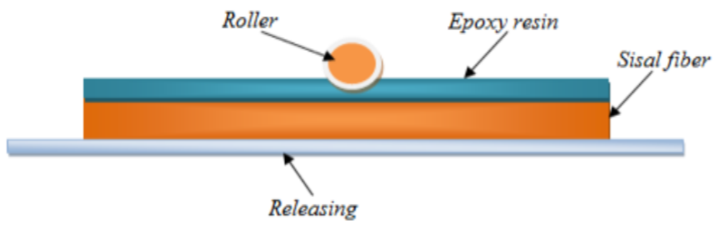


Figure 3. Sisal fiber reinforced epoxy composite molding sketch map.

(a) (b) (c) (d)

Figure 4. Sisal fiber-epoxy resin mixture in the mold surface, curing under 50MPa pressure at AAIT lab and typical view of composite board.

3.4. Experimental procedures

3.4.1. Dimension for test specimen

In order to evaluate the fracture toughness parameter, stress intensity factor of the chopped sisal fiber reinforced epoxy resin composites, the specimens for Compact Tension were machined from the laminates in accordance with the dimension given by ASTM D 5045-99 [11] as shown in Figure 5. The meaning of test methods and many conditions of testing are identical to ASTM E 399.

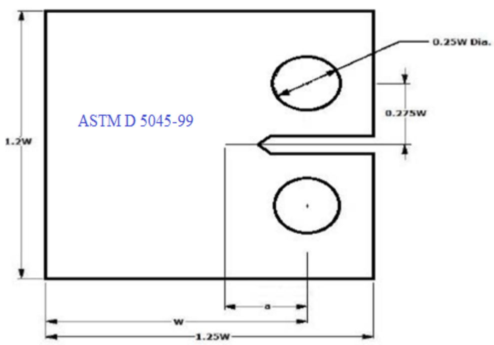
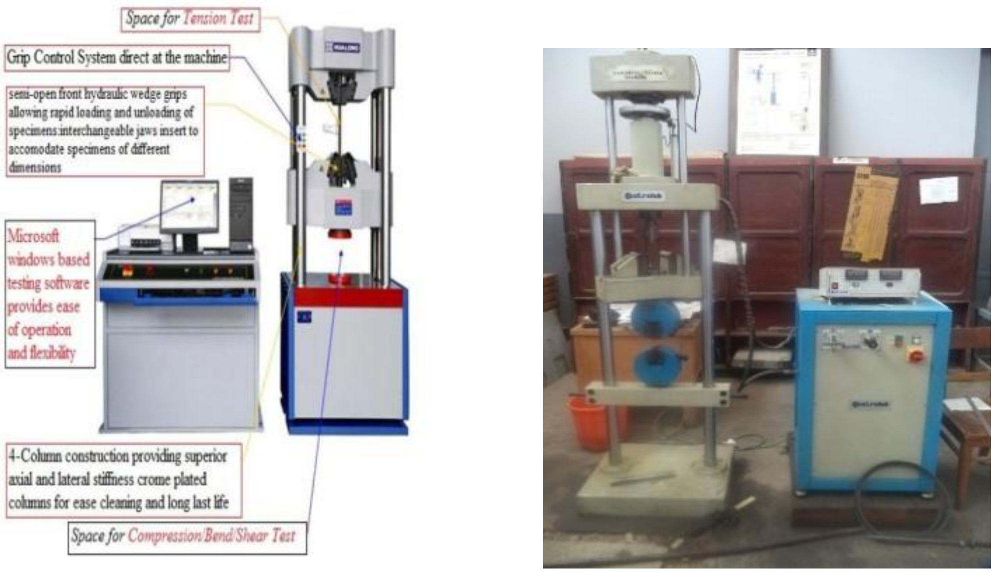


Figure 5. ASTM D 5045-99 standard for Compact tension specimen used for mode I fracture toughness test [11].

After the chopped sisal fiber reinforced epoxy composite specimens cut into the desired dimension based on the respective standards for each weight ratio of 15/85, 25/75, 30/70, 35/65, and 40/60, compact tension tests have been performed using UTM machine.

3.4.2. Introduction of test apparatus

Universal Testing Machine (UTM) Testing System: UTM Testing Systems are highly integrated testing packages that can be configured to meet different testing needs. Each includes a load unit with integrally mounted actuator and servo valves, a hydraulic power unit, and the control system, as illustrated in Figure 6. The control system has three major parts: the system software running on a personal computer, the digital controller, and a remote station control panel. These functions work together to provide fully automated test control. Optional application software packages let you further tailor the system to automate most any standard or custom test procedure.



(a) (b)

Figure 6. (a) Universal testing machine testing system working sketch map, (b) Universal testing machine in AAIT Lab.

3.4.3. Fracture toughness test for mode one fracture using compact tension test (ASTM D 5045-99)

Here compact tension samples were prepared with ratio value of 0.3 between crack length, "a" and crack width, "w" ($\frac{a}{w} = 0.3$). For each sample, three specimens were tested in the UTM machine and these CT specimens were connected with UTM machine by the help of attachment, which was made by the researcher in AAIT work shop. The cross head speed was 0.5 mm/min. Load and load line displacement (elongation) were recorded form the given test and stress intensity factor including critical one for the recorded loads. Typical CT specimen under compact tension test is shown in Figure 7a.

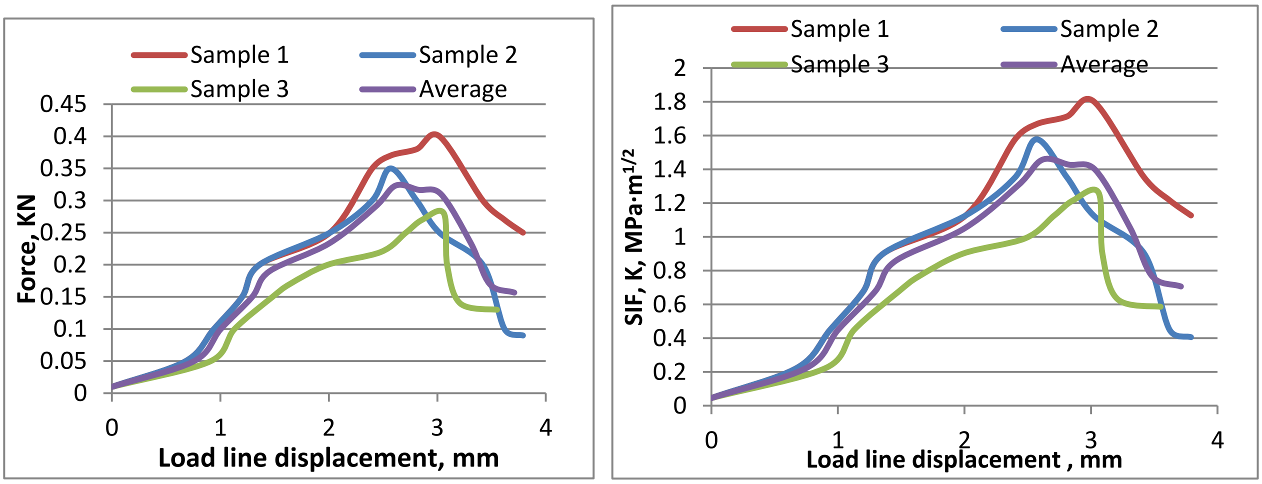
(a) (b)

Figure 7. (a) Typical CT specimen under compact tension test using UTM machine in AAIT lab, (b) sisal fiber reinforced epoxy composites after compact tension test.

4. Results and discussion

4.1. Compact tension test result

Five test samples of each mass composition of fiber and matrix for compact tension test were prepared. The experimental result of these specific tests have been summarized in Figures 8–13, which can relate different material properties that are used in fracture mechanics to show fracture resistant of a given composite, including stress intensity factors (SIF).



(a) (b)

Figure 8. Compact tension test result for the samples of 15/85 mass composition, (a) Force vs. Load line displacement, (b) Stress intensity factor vs. Load line displacement.

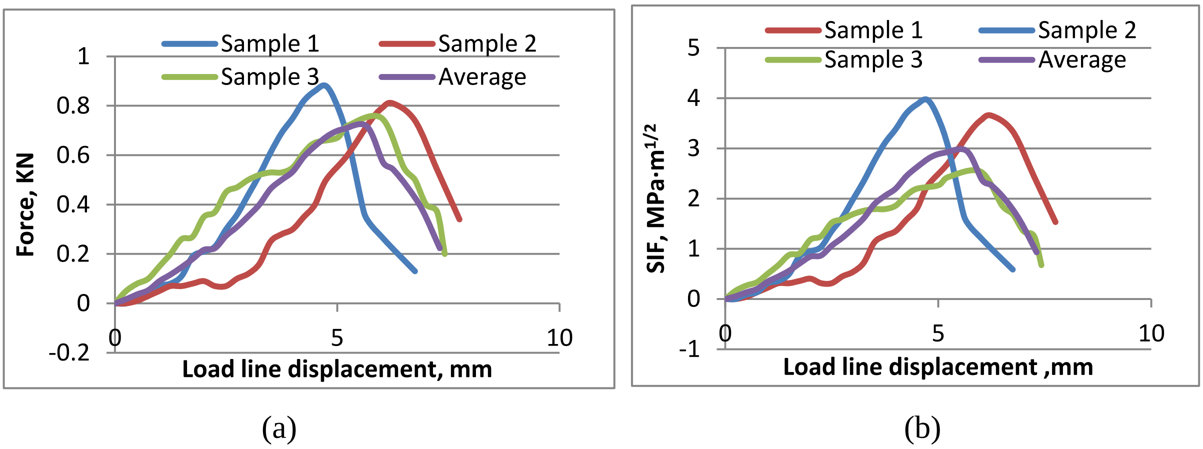


Figure 9. Compact tension test result for the samples of 25/75 mass composition, (a) Force vs. Load line displacement, (b) Stress intensity factor vs. Load line displacement.

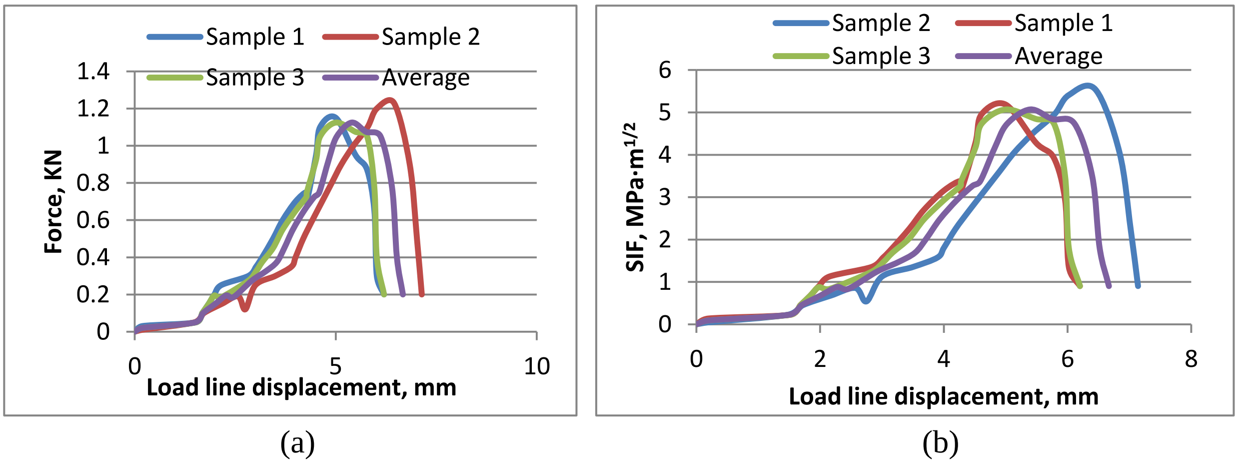


Figure 10. Compact tension test result for the samples of 30/70 mass composition, (a) Force vs. Load line displacement, (b) Stress intensity factor vs. Load line displacement.

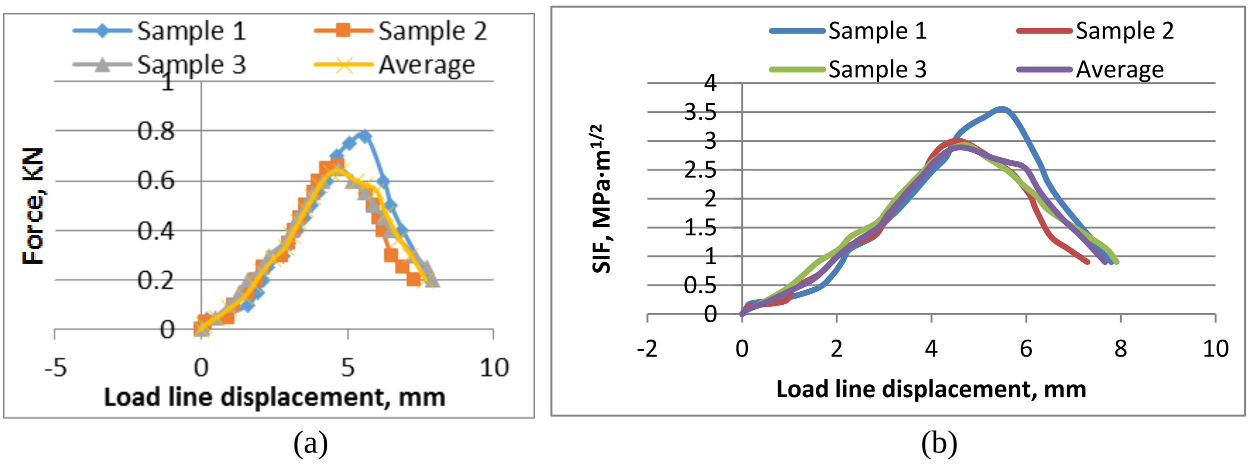
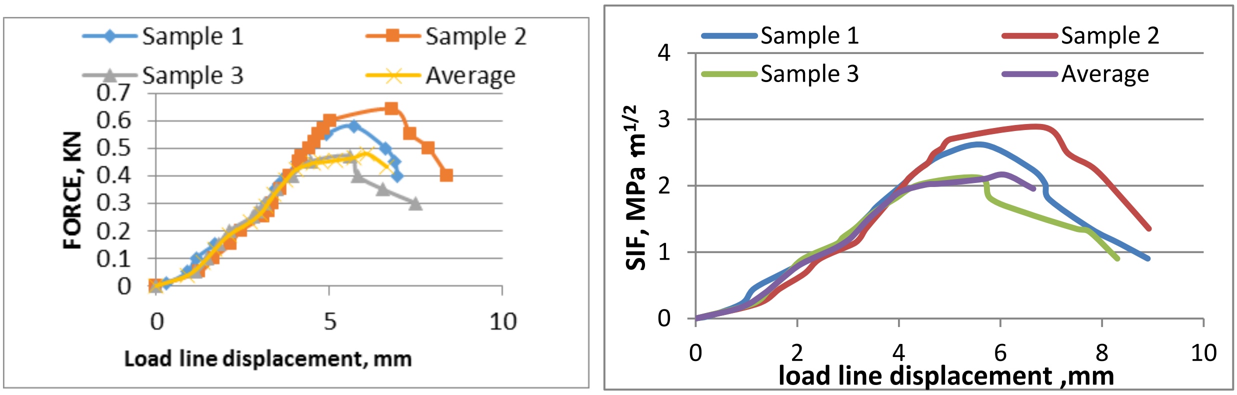


Figure 11. Compact tension test result for the samples of 35/65 mass composition, (a) Force vs. Load line displacement, (b) Stress intensity factor vs. Load line displacement.



(a) (b)

Figure 12. Compact tension test result for the samples of 40/60 mass composition, (a) Force vs. Load line displacement, (b) Stress intensity factor vs. Load line displacement.

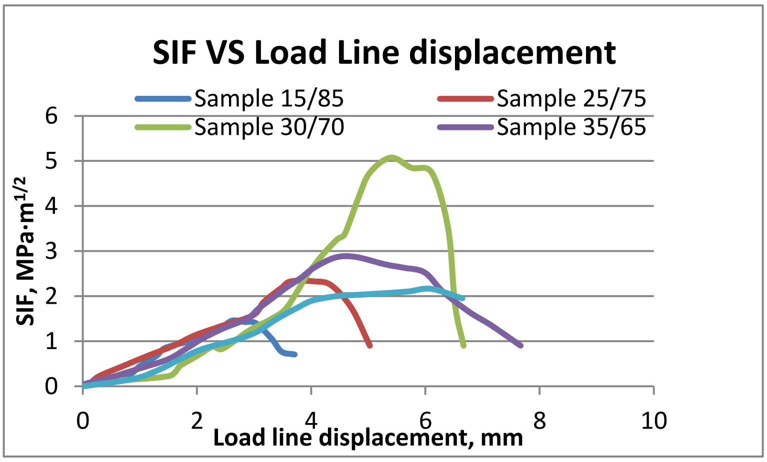


Figure 13. Compact tension test result for the samples of different mass composition, Stress intensity factor vs. Load line displacement.

4.2. Result discussion

The compact tension specimens were used to experiment the fracture toughness properties of epoxy and random chopped sisal fiber reinforced epoxy composites as it's given in Table 1 and summarized graphically as shown in Figure 14.

Table 1. Experimental results.

Designation	Maximum Load, N	Critical stress intensity factor(K_{IC}), MPa $m^{1/2}$
S15	470	2.19
S25	880	3.96
S30	1230	5.54
S35	780	3.5165
S40	640	2.88

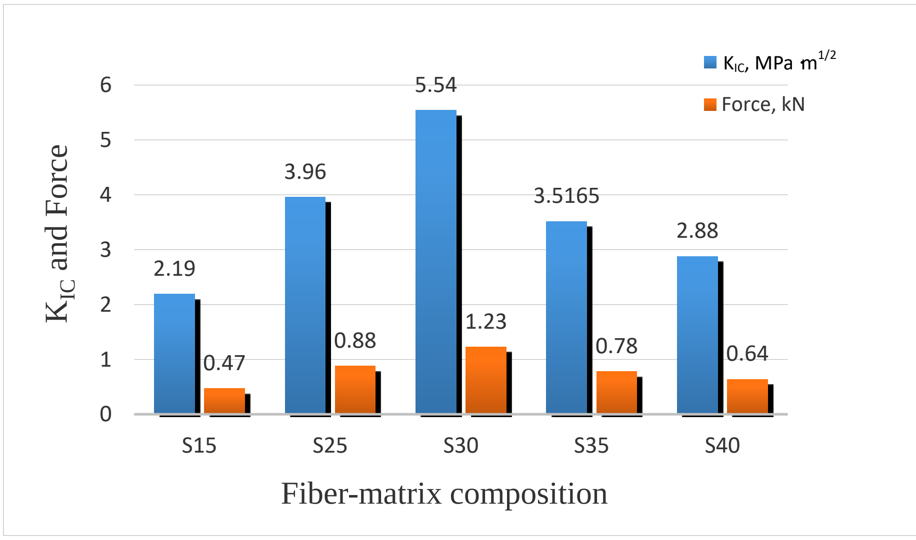


Figure 14. Experimental test result comparison for different fiber- matrix arrangement.

It is clearly observed from the experimental analysis which are shown in the above figures, the stress intensity factor is the main parameter to determine the fracture toughness. The fracture toughness increases with increasing sisal fiber content up to 30 wt%. The maximum values of load and critical stress intensity factor (K_{IC}) for the composite S30 are 1230 N and 5.54 MPa m$^{1/2}$. It is observed that the maximum values of load applied for the composite S30 is 62, 28, 37, and 48% more than those of composites S15, S25, S35 and S40 respectively, and critical stress intensity factor (K_{IC}) for the composite S30 is 60, 29, 37, and 48% more than those of composites S15, S25, S35 and S40 respectively. The critical strain energy release rate is calculated for all the composites and the maximum critical strain energy release rate for S30 is 13.72 MPa mm.

5. Conclusions

In this study, experimental analysis of sisal fiber based bio-composite was studied to find the composite with good fracture toughness through varying sisal fiber and epoxy ratios. Sisal fiber has already proven to be an excellent alternative natural fiber in composite, as it is abundant in Ethiopia in particular and all over the world in general, and fast growth with biodegradation. We try to identify the fracture toughness properties of chopped sisal fiber epoxy composite prepared by hand layup method with different composition as stated before. From the fracture test carried out on sisal fiber-epoxy composite using compact tension specimen and thoroughly evaluating the result obtained, it concluded that 30/70 mass composition has better mechanical and fracture property compared with other mass compositions. It can be used as reference for the other researchers to work on the mechanical properties of other sisal epoxy composites, and it can also be the base line for comparison of the research work of fracture toughness using finite element method. It can be improved through research work by changing the manufacturing techniques and changing size and orientation of fibers.

Conflict of interest

After we discuss in detail, we decide to declare that we have no conflicts of interest in this paper.

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