Facture Toughness Investigation of Chopped Sisal Fiber Reinforced Epoxy Resin Composite

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Candidate's Declaration

I hereby declare that the work which is being presented in this thesis entitled: "Fracture toughness investigation of chopped Sisal fiber Reinforced Epoxy Composite Material" is my own independent work, and has no previously been submitted to any other University in order to obtain a degree and that all sources of the material used for the thesis have been duly acknowledged. I further cede copyright of the dissertation in favor of Addis Ababa Institute of Technology.

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Yonas Tsegaye (Candidate) Date

This is to certify that the above declaration made by the candidate is correct to the best of my knowledge.

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Head of School: _________________ Signature: ________________Date:___________

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LIST OF ABBREVIATIONS AND ACRONYMS

ASTM	America Society for Testing and Material
CT	compact tension
EP	Epoxy Resin
FEA	finite element analysis
FEM	finite element method
FRP	Fiber Reinforced Polymer
G_I	strain energy release rate for mode one fracture
G_{IC}	critical strain energy release rate for mode one fracture
hr	hour
K_I	stress intensity factor for mode one fracture
K_{IC}	critical stress intensity factor for mode one fracture
m	meter
min	minute
mm	millimeter
nm	nanometer
NR	Natural rubber
PE	polyethylene
SFREC	Sisal fiber reinforced epoxy composite
ST	NaOH treated Sisal fiber reinforced epoxy composite sample
ST15	15%wt percent of NaOH treated sisal fiber reinforced epoxy composite
ST25	25%wt percent of NaOH treated sisal fiber reinforced epoxy composite

ST30	30%wt percent of NaOH treated sisal fiber reinforced epoxy composite
ST35	35%wt percent of NaOH treated sisal fiber reinforced epoxy composite
TPO	Thermoplastic Olefins
UP	Unsaturated Polyester
UTM	Universal Testing Machine

ABSTRACT

Natural fiber reinforced polymer matrix composites have found increasing attention from the recent decades because of its high strength to weight ratio, environmental friendliness, etc. Past studies show that synthetic and natural fiber such as glass, carbon, jute, hemp, banana etc., have been used in fiber reinforced polymer matrix composite. In this paper work, sisal fiber is used as reinforcement and an investigation has been carried out to make use of sisal fiber made epoxy resin matrix composite. Therefore, this work intends to study the fracture toughness analysis of chopped sisal fiber reinforced polymer matrix composite using finite element methods in terms of the linear elastic fracture mechanics, this includes the early investigations and recent advances of fracture toughness test methods which include the most important fracture mechanics parameters the so called stress intensity factor K.

The sisal fiber were extracted from Ethiopian highland sisal plant by retting and combing process manually and after extraction 10% sodium hydroxide was used for further surface treatment for the improvement of bond & interfacial shear strength of the sisal fiber. The fracture toughness test of chopped sisal fiber reinforced epoxy composite material were carried out using test samples which is prepared According to the ASTM standard. The specimen has been fabricated by using the epoxy resin (AY-105) as a matrix and the hardener (HY-905) 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 30 wt% chopped SFREC was found the high stress intensity factor and this result also compared and validated using FEM analysis and the error from the experiment is measures up to 1.08% for stress intensity factor and 2.286% for strain release rate. This signifies the validity of the experiment.

Furthermore, both results justify that the 30/70 composition of chopped sisal fiber and epoxy resin matrix has robust fracture characteristics with K_{IC} of 5.48 MPa.m1/2 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.

Key words: sisal fiber, epoxy, composite, hand layup, stress intensity factor (K_{IC}), strain energy release rate (G_{IC}), FEM

Chapter 1. Introduction

1.1 Background

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 interface 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.

Composite materials especially the fiber reinforced polymer (FRP) kind highlight how different materials can work in synergy. Analysis of these properties shows that they depend on:-

1) The properties of the individual components;
2) The relative amount of different phases;
3) The orientation of various components; the degree of bonding between the matrix and the reinforcements and
4) The size, shape and distribution of the discontinuous phase. The material involves can be organics, metals or ceramics. Therefore, a wide range of freedom exists, and composite materials can often be designed to meet a desired set of engineering properties and characteristics [1]

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 purposes. Particularly their strength and stiffness are near to the ground compared to metals and ceramics. These difficulties are surmounting by reinforcing other materials with polymers. Secondly the processing of polymer matrix composites doesn't require high pressure and high temperature. And also 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 manly used for different engineering application, predominantly for the development of the interior panel of automobiles. Common fiber 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 confirm advanced mechanical properties like stiffness, flexibility and modulus composite to glass fibers [6].

Their availability, renewability, low density, and price as well as acceptable mechanical properties make natural fibers more attractive ecological alternative to glass, carbon and man-made fibers used for the manufacturing of composites.

The natural fiber containing composites are more environmentally 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 limitation with natural fibers such as their poor mechanical properties and high moisture absorption [7].

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 for measures of material resistance to extension of a crack. It is constrained to results of fracture mechanics tests in this work, which are directly relevant to fracture control and to fracture test in telling the material property for a crack to resist fracture. 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. Prasad et al. 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 at. Introduce 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. 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 (KIC).

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 [8].

In this paper, fracture behavior of chopped sisal fiber reinforced epoxy polymer matrix composite has been studied. The analysis is carried out by FEA and it will validate with experimental results.

1.2 Problem statement

A report by FAOSTAT, 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 to reinforcing polymers to form a composite materials.

Composite designers and engineers recognize delamination as a primary failure mode. Unfortunately, modeling and predicting this behavior is not easy. Although sisal fiber reinforced polymer composite has several advantages including: low weight, low cost, high availability, easy productivity, friendliness to environment and high specific mechanical performance than glass and carbon fibers, determining fracture toughness of sisal fiber reinforced polymer composite is very important, because fracture toughness test tell as the material property for a crack to resist fracture.

In general, designers and engineers have the ability to implement a stress analysis and utilize this in parallel with empirically obtained strength data. In the case of engineering composites, fracture toughness is not as easily accounted for.

The goal of the current study is to provide a systematic engineering approach to help develop laminated architectures, evaluate inter-laminar fracture properties, and improve performance of engineering composites in commercial applications.

Moreover, Fracture toughness determination of sisal fiber reinforced polymer composite can be conducted experimentally, but in Ethiopia, such experimental setups are not yet available. Even if it is available, it is very expensive to conduct such estimation experimentally.

Therefore, by using computational method such as FEM analysis one can easily estimate the required mechanical properties as well as simulate using FE software such as ABAQUS and compare it with the corresponding experimental results.

1.3 Objective

1.3.1 General objective

The general objective of this thesis is to study the fracture toughness analysis of chopped sisal fiber reinforced polymer matrix composite (2D analysis) using finite element methods for Mode l fracture.

1.3.2 Specific objective

- Selection of sisal with better mechanical characteristics that give better fiber properties
- Determination of fiber and matrix contents of the composite
- Refining the extraction, preparation and chemical treatment procedures of sisal reinforced epoxy laminates
- Investigation of fracture toughness.

1.4 Scope and Limitation of the Study

1.4.1 Scope

This research is undertaken to investigate the effect of loading condition in composite materials containing natural fiber (chopped sisal fiber) and consequent FEM analysis using ABAQUS to study the fracture toughness analysis which would allow further users to look into the corresponding effects related to these properties.

1.4.2 Limitation

The simulation will be performed using commercial computational software. In order to get more accurate result the different version of licensed commercial software which is applicable for FEM simulation can be implemented and the results can easily be validated for the purpose convenience.

1.5 Thesis Organization

This report focuses on the fabrication and fracture toughness characterization of chopped sisal fiber reinforced epoxy composite, and results discussion. The manuscript comprises of Six-chapters.

Chapter 1: Introduces the background of natural fiber composite materials and this project's objectives. Problem Statement, Scope and limitations

Chapter 2: Reviewed all relevant research papers regarding natural fiber composite materials, ranging from polymer types, fiber types, and composite's chemical, mechanical properties. Recent researches on sisal fiber reinforcement on polymers are widely and deeply reviewed.

Chapter 3: This chapter states different Theory's which are used for the predication of fracture mechanics parameters for both experiment and FEM analysis cases.

Chapter 4: Experimental and FEM deals with the fracture toughness Properties characterization for chopped sisal fiber reinforced epoxy composite. In this chapter the methods, materials for the preparation of test specimen discussed and also the fracture toughness Properties investigation designs plan for both the experimental and FEM analysis, which used for the investigation of stress intensity factor and strain energy release rate of chopped sisal fiber reinforced epoxy composites, has been discussed.

Chapter 5: result and discussion, here the Characterization of composite material; the fracture toughness Properties, are performed well and discussed in detail.

Chapter 6: This chapter is dedicated to the conclusion and future work of this thesis.

Chapter Two - Literature Review

2.1 Composite Materials

A composite is a material prepared by combining two or more different materials in such a way that the resultant material is capable with properties advanced to any of its parental ones. Their advanced properties are usually applied in different fields like defense, aerospace, automobile, engineering applications, sports goods, etc. Nowadays, natural fiber composites are highly required because of their eco-friendly properties. Natural fibers such as sisal and bamboo have the potential to be used as a replacement for traditional reinforcement materials in composites for applications which requires high strength to weight ratio and further weight reduction. Natural fibers such as jute, sisal, bamboo, and silk are inexpensive, abundant and renewable, lightweight, with low density, high toughness, and biodegradable.

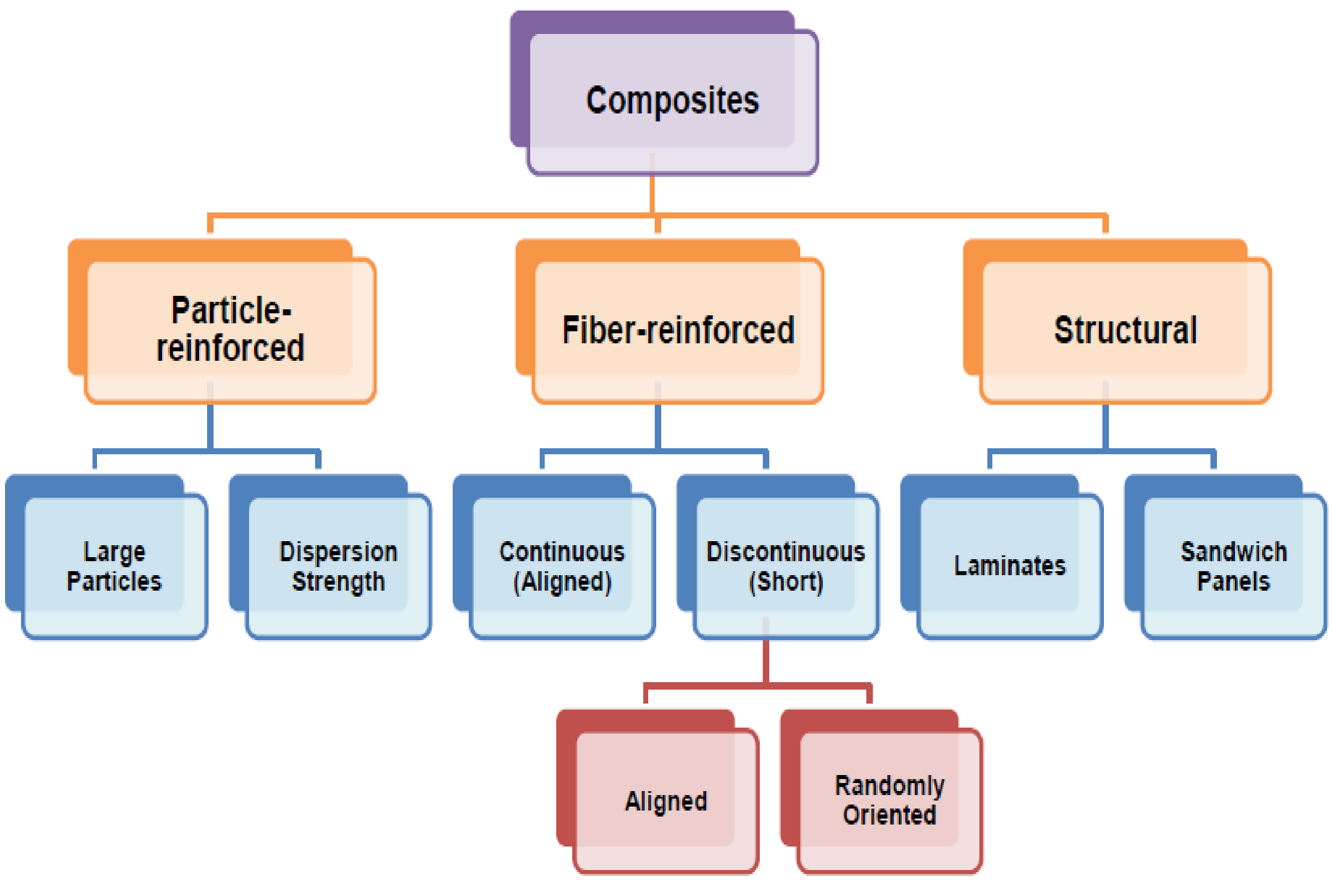


Figure 1. Composite classification

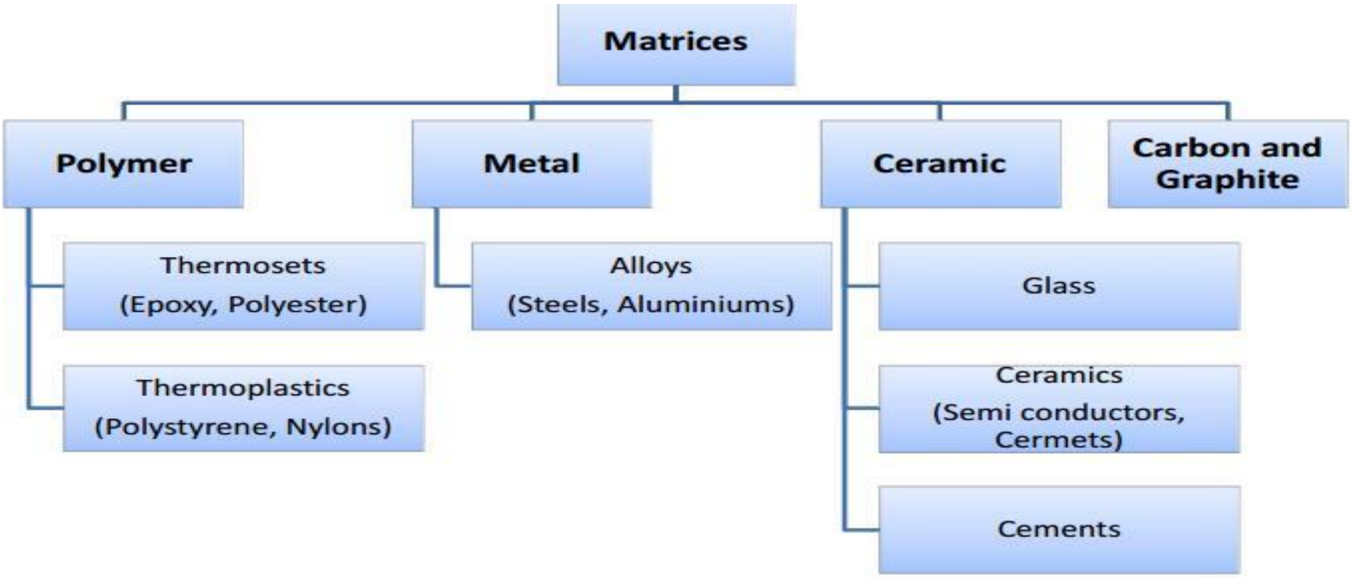


Figure 2. Classification of matrices

2.2 Natural Fiber

Natural fiber is a type of renewable sources and a new generation of reinforcements and supplements for polymer based materials. The development of natural fiber composite materials or environmentally friendly composites has been a hot topic recently due to the increasing environmental awareness.

Natural fiber reinforced polymer composites have raised great attentions and interests among materials scientists and fascinate design engineers in recent years due to the considerations of developing an environmental friendly material and partly replacing currently used glass or carbon fibers for reinforcing composites. The application of natural fiber reinforced polymer composites and natural-based resins for replacing existing synthetic polymer or glass fiber reinforced materials in huge. Automotive and aircrafts industries have been actively developing different kinds of natural fibers, mainly on hemp, flax and sisal and bio resins systems for their interior components. They are high specific strength and modulus materials, low prices, recyclable, easy available in some countries, etc.

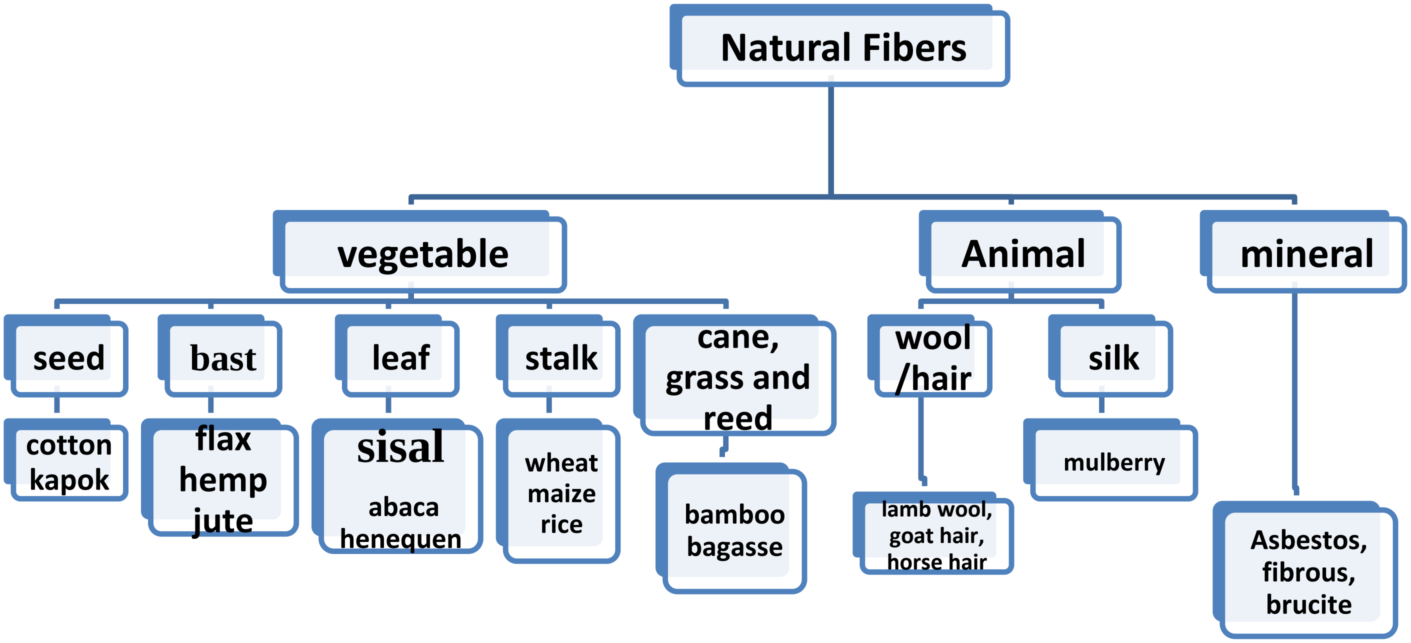


Figure 3. Natural fiber classification

2.2.1 Sisal Plant

Sisal or sisal hemp (Scientific name is Agave sisalana) is an agave. Agave sisalana of Agavaceae (Agave) that yields a stiff fiber used in making rope. Though native to tropical and sub-tropical North and South America, sisal plant is now widely grown in tropical countries of Africa, the West Indies and the Far East [15]. A sketch of a sisal plant is shown in the figure 4 and sisal fibers are extracted from the leaves of this plant.

A good sisal plant has a 7-10 year life-span and typically produces or yields about 200-250 leaves with each leaf having a mass composition of 4% fiber, 0.75% cuticle, 8% other dry matter and 87.25% moisture (water). Thus a normal sisal plant leaf weighing about 600g yields about 3% by weight of fiber with each leaf containing about 1000 fibers [16].

The other important feature of sisal plant is that its cultivation process is very ease and also it can grow in all kinds of environment [17].

Figure 4. A typical view of sisal plant

2.2.2 Sisal Fiber

Sisal fibers are obtained or extracted from the leaves of sisal plant called Agave sisalana, which was originated from mexico, and is now mainly cultivated in east Africa, Brazil, Haiti, India and Indonesia. It is grouped under the broad heading of the "hard fibers" among which sisal fiber is the second most durable and strong [18]. The fibers are extracted through hand extraction machine composed of serrated knives. The peel is clamped between the wood plank and knife and hand-pulled through, removing the resinous material.

The extracted fibers are sun-dried which whitens the fiber. Once dried, the fibers are ready for knotting. A bunch of fibers are mounted or clamped on a stick to facilitate segregation.

Figure 5. A typical view of sisal fiber

The chemical compositions of sisal fibers have been reported by several groups of researchers for example, Wilson [18] indicated that sisal fiber contains 78% cellulose, 8% lignin, 10% hemi-celluloses, 2% waxes and about 1% ash by weight; but Rowell [20] found that sisal contains 43±56% cellulose, 7±9% lignin, 21±24% pentosan and 0.6±1.1% ash. More recently, Joseph et al.[23] reported that sisal contains 85±88% cellulose. These large variations in chemical compositions of sisal fiber are a result of its different source, age, measurement methods, etc. Indeed, Chand and Hashmi [24] showed that the cellulose and lignin contents of sisal vary from 49.62±60.95 and 3.75±4.40%, respectively, depending on the age of the plant. The length of sisal fiber is between 1.0 and 1.5 m and the diameter is about 100±300 mm [20]. The fiber is actually a bundle of hollow sub-fibers. Their cell walls are reinforced with spirally oriented cellulose in a hemi-cellulose and lignin matrix. So, the cell wall is a composite structure of lingo-cellulosic material reinforced by helical micro-fbrillar bands of cellulose. The composition of the external surface of the cell wall is a layer of lignaceous material and waxy substances which bond the cell to its adjacent neighbors'. Hence, this surface will not form a strong bond with a polymer matrix. Also, cellulose is a hydrophilic glucan polymer consisting of a linear chain of 1, 4-b bonded an hydro glucose units [25] and this large amount of hydroxyl groups will give sisal fiber hydrophilic properties. This will lead to a very poor interface between sisal fiber and the hydrophobic matrix and very poor moisture absorption resistance.

Physical property sisal fiber Density (g/cm3) 1.41 Elongation at break (%) 6–7 Cellulose content (%) 60–65 Young's modulus (GPa) 12.8 Diameter (μm) 205–230

2.3 Matrix and Its Type

Odian 2004 [26] has described polymers as large molecule having numerous frequent subdivisions. Synthetic polymers and natural polymers are the major types of the polymers. Human life is very evident with both types of polymers, e.g., a human fabricated polymer, polyethylene (PE) is used in the supermarket shopping bag, the NR (natural rubber) is being used in the types of our cars and the NR is believed to be a natural product produced from the rubber tree [27]. Before the development of polymer science and engineering around 1900s, many kinds of polymer materials were existed, such as: Natural polymers which cover: amber, shellac, wool, silk, and cellulose. Whereas Synthetic polymers cover: Phenol formaldehyde resin, Synthetic rubber, Nylon, Neoprene, chloride, Polyvinyl , Polyethylene, Polystyrene, Polypropylene, Epoxy resin, and Poly acrylo nitrile [28]. The polymer is divided into two different categories thermosets and thermoplastic and application of thermosets is mentioned below [29].

2.3.1 Epoxy Resin

Thermosets

They are described as a polymer that transforms conclusively into an insoluble network structure through remedial measures and develops into a soft solid position. Heating or a suitable radiation is likely to prompt the curing. A cross-linking structure will eventually be emerged through the curing procedure, by which the resin is transformed into rubber or plastic. Because, the thermosets are having 3D cross-link configuration, so they are normally robust than thermoplastics, and are desirable for high-temperature applications. But, their heavy brittleness than thermoplastics is one of the problems. Epoxy resin and unsaturated polyester are extensively used materials among all the thermosets materials [30].

- **Unsaturated Polyester (Abbreviation: UP)**

When dibasic organic acids are reacted with polyhydric alcohols, we obtain the unsaturated polyester resins, which are applied in bulk molding compound, sheet molding compound and in the toner of laser printers [31].

- **Epoxy Resin (Abbreviation: EP)**

The epoxide functional group is enclosed in the epoxy that is a preserved thermoset resin. Before use, the hardener (which cures epoxy resin) and epoxy resin are usually blended together. Many industries observe the use of Epoxy, e.g., structural adhesives electronic and electrical components, metal coatings, fiber-reinforced plastic materials and high tension electrical insulators [32].

2.4 Previous Research Works

A lot of work has been done by researchers based on these natural fibers. Some of them are reviewed as follows:

Li et al. Conducted a research to study the mechanical properties, especially interfacial performances of the composites based on natural fibers due to the poor interfacial bonding between the hydrophilic natural fibers and the hydrophobic polymer matrices. Two types of fiber surface treatment methods, namely chemical bonding and oxidization were used to improve the interfacial bonding properties of natural fiber reinforced polymeric composites. Interfacial properties were evaluated and analyzed by single fiber pull-out test and the theoretical model. The interfacial shear strength (IFSS) was obtained by the statistical parameters. The results were compared with those obtained by traditional ways. Based on this study, an improved method which could more accurately evaluate the interfacial properties between natural fiber and polymeric matrices was proposed.

Joshi et al . Compared life cycle environmental performance of natural fiber composites with glass fiber reinforced composites and found that natural fiber composites are environmentally superior in the specific applications studied. Natural fiber composites are likely to be environmentally superior to glass fiber composites in most cases for the following reasons:

(1) natural fiber production has lower environmental impacts compared to glass fiber production;

(2) natural fiber composites have higher fiber content for equivalent performance, 16 reducing more polluting base polymer content;

(3) The light-weight natural fiber composites improve fuel efficiency and reduce emissions in the use phase of the component, especially in auto applications; and

(4) End of life incineration of natural fibers results in recovered energy and carbon credits.

Jackson D. Megiatto Jr. et al. studied the optimized process parameters such as pressure, temperature and time interval were varied for manufacturing thermo set phenolic composites reinforced with sisal fibers. he clearly showed that the increase in temperature decrease the time required for saturation of the composite sample, increasing of the molding pressure at the gel point of the matrix increase the impact strength of the material and also the application of higher values of the pressure at the initial stage of the cure cycle probably hindered the vaporization of the water generated as the a byproduct of the cure reaction, the improved filling of the fiber pores can be done by increasing the inter diffusion of the phenolic matrix through the sisal fibers, using higher values of pressure before the gel point of resin.

Shah and Lakkad tries to compare the mechanical properties of jute-reinforces and glass-reinforced and the results shows that the jute fibers, when introduced into the resin matrix as reinforcement, considerably improve the mechanical properties, but the improvement is much lower than that obtained by introduction of glass and other high performance fibers. Hence, the jute fibers can be used as reinforcement where modest strength and modulus are required.

Another potential use for the jute fibers is that, it can be used as a „filler" fiber, replacing the glass as well as the resin in a filament wound component.

The main problem of the present work has been that it is difficult to introduce a large quantity of jute fibers into the JRP laminates because the jute fibers, unlike glass fibers, soak up large amount of resin. This problem is partly overcome when “hybrid sing‟ with glass fibers is carried out.

M.Ramesh et al. fabricated hybrid fiber composites–polyester reinforced by sisal fiber, jute fiber and glass fiber, and evaluated their mechanical properties such as tensile strength, flexural strength and impact strength. It is found that the sisal fiber and jute fiber are able to alternate glass fiber to reinforce polyesters and improved their flexural and tensile strength. SEM results also revealed the breakage occurred in the sisal/jute fibers (Ramesh, Palanikumar& Reddy 2013).

Monteiro SN. Rodriquez *et al*. tries to use the sugar cane bagasse waste as reinforcement to polymeric resins for fabrication of low cost composites. They reported that composites with homogeneous microstructures could be fabricated and mechanical properties similar to wooden agglomerates can be achieved.

bisanda et al,1991 have studied the effect of saline treatment and alkali treatment on the mechanical and physical properties of sisal epoxy composites. They have reported the treatment of sisal fiber with saline produced by mercerization provides improved wet ability mechanical properties and wear resistance; mercerization and saline treatment improve the compressive strength without significant effect on flexural property of dry sisal composite.

Paramasivam & Abdulkalam (1974) have investigated the feasibility of developing polymer based composites using sisal fibers due to the low cost production of composites and amenability of these fibers to winding, laminating and other fabrication it was found that the fabrication of these composites was fairly easy and cost production was quite low winding of cylinders with longitudinal or helical and hoop reinforcement was successfully carried out. Tensile strength of sisal epoxy composites was found to be 250-300MPa, which was nearly half the strength of fibers glass-epoxy composites of the same composition. Because of low density of sisal fiber however, the specific strength of sisal composites was comparable with that of glass composites the unidirectional modulus of sisal-epoxy composites was found to be about 8.5GPa.

After reviewing the existing literature available on natural fiber composites, particularly natural fibers (jute, sisal, bamboo, bagasse and lantana camara) composites put efforts to understand the basic needs of the growing composite industry. The conclusions drawn from this is that, the success of combining vegetable natural fibers with polymer matrices results in the improvement of mechanical properties of the composites compared with synthetic fiber reinforced polymer matrix composite materials. These composite fibers are cheap and nontoxic, can be obtained from renewable sources, and are easily recyclable. Moreover, despite their low strength, they can lead to composites with high specific strengths because of their low density.

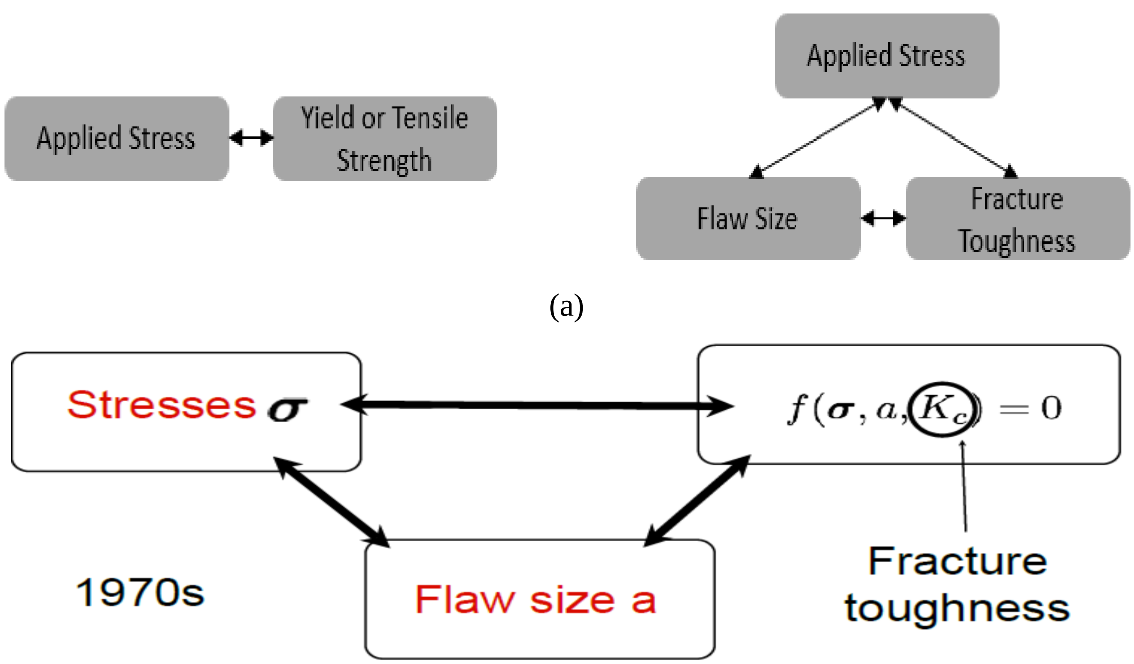
Chapter Three: Theory

3.1 Fracture Mechanics

Fracture mechanics is the field of mechanics concerned with the study of the propagation of cracks in materials. A **fracture** is the (local) separation of an object or material into two, or more, pieces under the action of stress. It uses methods of analytical solid mechanics to calculate the driving force on a crack and those of experimental solid mechanics to characterize the material's resistance to fracture. In general two forms of failure in solids exist, permanent (plastic) deformation and breakage, the classical failure theory describe failure of a structure due to the relation between applied stress and yield or tensile strength, as shown in figure below.

For the fracture mechanics three important variables are pronounced, a combination between the applied stress, flaw size and the fracture toughness that replace the strength determine whether or not the structure leads to failure.[10]

New failure analysis



(b)

Figure 6. Relation of Classical failure theory, Relation of Fracture mechanics

Fracture mechanics play a vital role in the design of every critical structure or machine component in which durability and reliability are important issues (aircraft components, nuclear pressure vessels, microelectronic devices). It has also a valuable tool for material scientists and engineers to guide their efforts in developing materials with improved mechanical properties.

The classical failure theory assumes that no defects exist in the material and for a plate affected by a uniform load a corresponding uniform stress variation is introduced, see Figure 7a. During materials manufacturing, processing and service a flaw or crack is introduced and a local stress concentration is presented. In Figure 7b the plate is affected by a crack that produces a stress concentration or singular stress field [9]

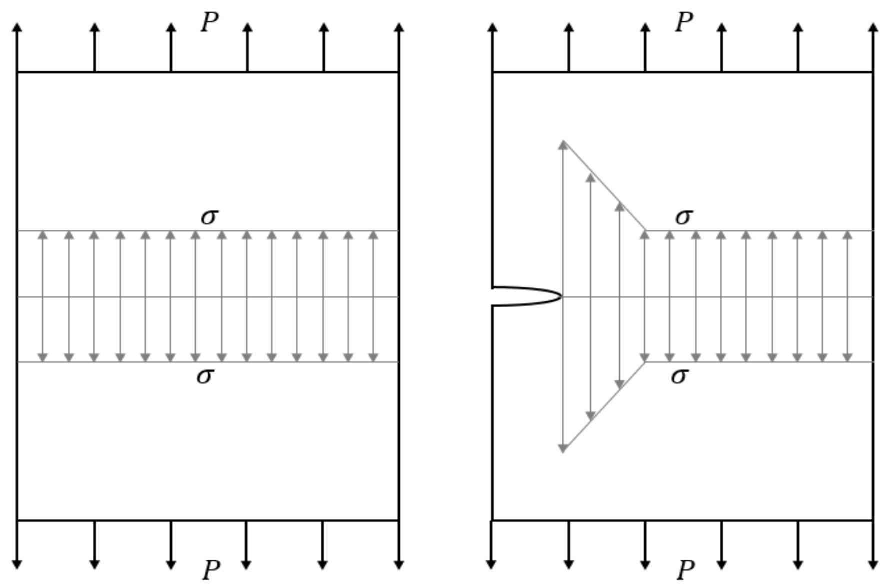


Figure 7 (a) Plate with uniform distributed stress, (b) Cracked plate with stress concentrations [9]

A. The plate affected by a uniform stress field is described by criteria from e.g. Von Misses, and compared with the yield stress in order to see if failure occurs.
B. The local stress concentrations field in the cracked plate is varying by a singularity at the crack-tip. In order to determine this singular stress field the fracture mechanism is taking into account [9].

For the classical failure theory yield criterion is introduced in order to obtain failure behavior, for fracture mechanics a corresponding value is taking into account, to determine when fracture occur, this value is the fracture toughness.

In this master thesis, the LEFM approach is taking into account in order to determine the crack propagation trajectories, and to investigate facture toughness, and it is assumed that the material obtain homogenous and isotopic behavior.

3.2 Linear Elastic Fracture Mechanics

For any homogeneous and isotropic material, stress surrounding the crack tip is often analyzed assuming linear elastic material behavior [5]. The method of linear elastic fracture mechanics assumes the plastic region near crack tip is much smaller than the dimensions of the crack and the structural member. This is a very important concept, scientists and engineers call it small-scale yielding [5], for simplifying the stress analysis near crack tip. Assuming the geometry has very small displacement and the material is elastic, homogeneous and isotropic.

3.2.1 Stress Distribution around a Crack

The cracks in mechanical components subject to applied loads behave very close to what is observed when there are notches, which are responsible for stress concentration due to reduction of area against the nominal area. The geometry of the crack creates high stress concentrations in its tip. This behavior is illustrated in figure below. Due to the high-tension observable on the edge of the crack, a plastic zone appears. However, following the LEFM theory, the plastic behavior is not taken into account, and tension is given by an ideal crack following the linear elastic model. Consequently, the LEFM reveals a large gap, by not taking into account areas that could be in the plastic domain [10].

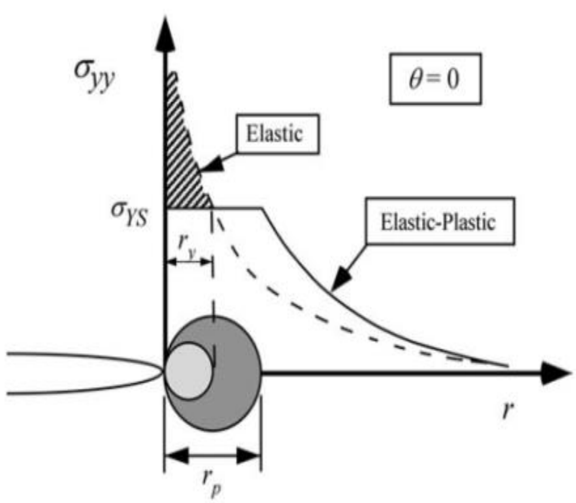


Figure 8. Real and ideal crack tension behavior [10]

Consulting Anderson [10], for cracked geometries subjected to external forces, it is possible to derive closed- forms or analytical expressions for the stresses in the body, assuming the LEFM. Irwin [11],Sneddon [12], Westergaard [13], and Williams [14] were among the first to publish such solutions.

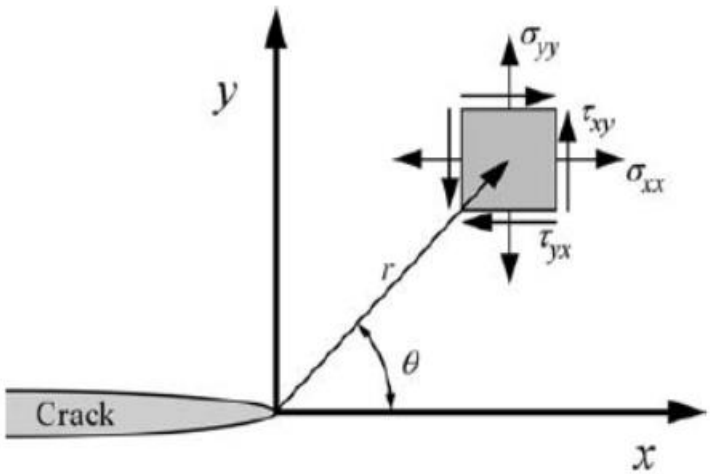


Figure 9. Stresses near the crack tip and polar coordinates [10]

Considering a polar coordinate system, (*r; θ*), with the origin at the crack tip represented on figure above, it can be shown that the stress field in any linear elastic cracked body is given by,

$$\boldsymbol{\sigma_{i,j} = \left(\frac{k}{\sqrt{r}}\right) f_{i,j}(\theta) + \sum_{m=0}^{\infty} A_m r^{\frac{m}{2}} g_{i,j}^{m}(\theta)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textit{Equation 1}$$

Where: $\sigma ij$is the stress tensor,

*K*a constant and *fij*a dimensionless function of *θ* in the leading term.

For the higher-order terms, $A_m$is the amplitude and a dimensionless function of *θ* for the m^{th}term. It should be noticed, that the solution for any given configuration contains a leading term that is proportional to $\frac{1}{\sqrt{r}}$. As *r approaches to* 0, the leading term goes to infinity, but the other terms remain finite or approach zero. Thus, stress near the crack tip varies with$\frac{1}{\sqrt{r}}$., independently of the geometries. It canalso be shown that displacement near the crack tip varies with$\sqrt{r}$. The above Equation describes also a stress singularity, since stress is asymptotic to *r* = 0.

Fracture modes

Fracture is separation of a body in to pieces due to stress at temperature below the melting point.

Steps in fracture — **Crack formation** / Crack propagation

Depending on the ability of material to undergo plastic deformation before the fracture two fracture modes can be defined as ductile or brittle.

The stress field near crack tips can be categorized as mode I: opening mode, mode II: sliding and mode III: tearing. (Crack tip stress distribution by Irwin : (based on elastic theory))

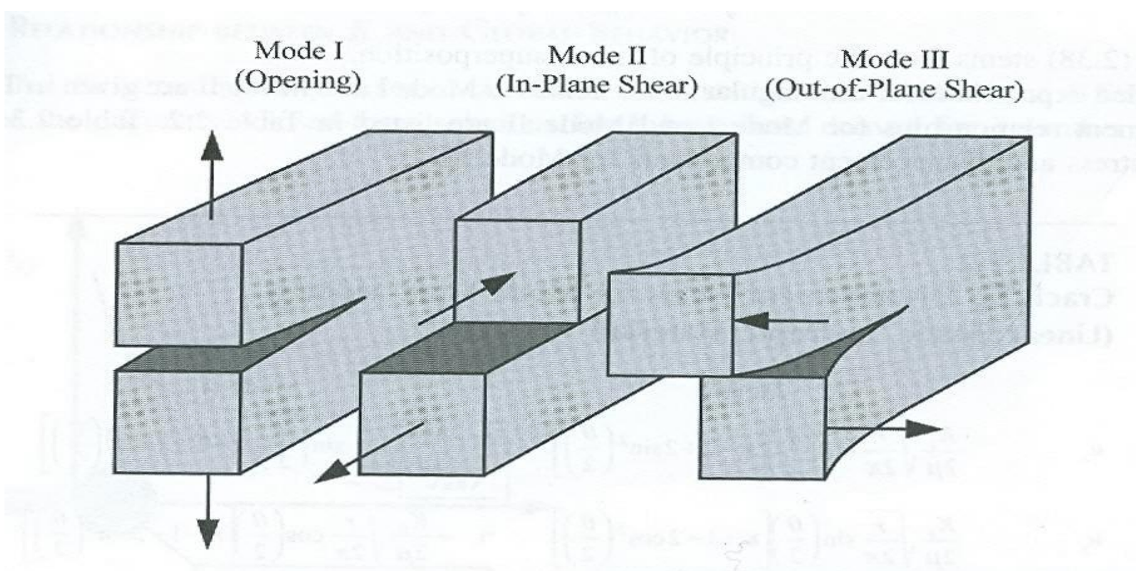


Figure 10 fracture modes

A cracked body can be loaded in any one of these modes, or a combination of two or three modes. For each of these modes, it can be deduced a stress intensity factor, which are presented next.

3.2.2 Stress Intensity Factors (SIF)

The stress intensity factors are used as a measure that quantifies the severity of a crack relatively to others cracks [10]. They are so, of extreme importance for the cracks study. They are also related to the mechanisms of crack initialization but also their propagation, and in some cases, the stress intensity factor may reach an extreme value: the fracture toughness K_C, leading to the fracture of the components.

According to the linear elastic fracture mechanics (LEFM), the behavior of a crack in any brittle material can be characterized completely by a single parameter known as the stress intensity factor (SIF).

The Governing equations for linear elastic analysis in 2-D is:

1. The strain – displacement relationships

$$\varepsilon_{xx} = \frac{\partial u_x}{\partial x} \qquad \varepsilon_{yy} = \frac{\partial u_y}{\partial y} \qquad \varepsilon_{xy} = 1/2(\frac{\partial u_x}{\partial y} + \frac{\partial u_y}{\partial x}) \ldots\ldots\ldots \textit{Equation 2}$$

2. The stress – strain relationships

i. For plane strain, where $\varepsilon_{zz} = \varepsilon_{xz} = \varepsilon_{yz} = \tau_{xz} = \tau_{yz} = 0$

$$\sigma_{xx} = \frac{E}{(1+\nu)(1-2\nu)}\{(1-\nu)\varepsilon_{xx} + \nu\varepsilon_{yy}\} \ldots\ldots\ldots \textit{Equation 3}$$

$$\sigma_{yy} = \frac{E}{(1+\nu)(1-2\nu)}\{(1-\nu)\varepsilon_{yy} + \nu\varepsilon_{xx}\} \ldots\ldots\ldots \textit{Equation 4}$$

$$\tau_{xy} = 2G\varepsilon_{xy} = (\frac{E}{(1+\nu)})\varepsilon_{xy} \ldots\ldots\ldots \textit{Equation 5}$$

$$\sigma_{zz} = \nu(\sigma_{xx} + \sigma_{yy}) \ldots\ldots\ldots \textit{Equation 6}$$

ii. For plane stress, where $\sigma_{zz} = \varepsilon_{xz} = \varepsilon_{yz} = \tau_{xz} = \tau_{yz} = 0$

$$\sigma_{xx} = \frac{E}{1-\nu^2}\{\varepsilon_{xx} + \nu\varepsilon_{yy}\} \ldots\ldots\ldots \textit{Equation 7}$$

$$\sigma_{yy} = \frac{E}{1-\nu^2}\{\varepsilon_{yy} + \nu\varepsilon_{xx}\} \ldots\ldots\ldots \textit{Equation 8}$$

$$\tau_{xy} = 2G\varepsilon_{xy} = (\frac{E}{(1+\nu)})\varepsilon_{xy} \ldots\ldots\ldots \textit{Equation 9}$$

$$\varepsilon_{zz} = \frac{-\nu}{(1-\nu)}\{\varepsilon_{xx} + \varepsilon_{yy}\} \ldots\ldots\ldots \textit{Equation 10}$$

The equilibrium equations:

$$\frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} = 0 \ldots\ldots\ldots \textit{Equation 11}$$

$$\frac{\partial \sigma_{yy}}{\partial y} + \frac{\partial \tau_{xy}}{\partial x} = 0 \ldots\ldots\ldots \textit{Equation 12}$$

And the compatibility equation

$$\left[\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right](\sigma_{xx} + \sigma_{yy}) = 0 \ldots\ldots\ldots \textit{Equation 13}$$

The Airy stress function $\emptyset$ can satisfy all the governing equations and is used to derive the stress field near the crack tip.

$$\emptyset = \frac{K_I}{3\sqrt{2\pi}} r^{3/2}\{cos\frac{3\theta}{2} + 3\,cos\,\theta/2\} \ldots \quad \textit{Equation 14}$$

$$\frac{\partial^4\emptyset}{\partial x^4} + 2\frac{\partial^4\emptyset}{\partial x^2\partial y^2} + \frac{\partial^4\emptyset}{\partial y^4} = 0 \ldots \quad \textit{Equation 15}$$

Solving the above equation yields the stress fields for mode I as:

$$\sigma_x = \frac{K_I}{\sqrt{2\pi r}} cos\,\theta/2\,\{1 - sin\frac{\theta}{2} * sin\,3\theta/2\} \ldots \quad \textit{Equation 16}$$

$$\sigma_y = \frac{K_I}{\sqrt{2\pi r}} cos\,\theta/2\,\{1 + sin\frac{\theta}{2} * sin\,3\theta/2\} \ldots \quad \textit{Equation 17}$$

$$\tau_{xy} = \frac{K_I}{\sqrt{2\pi r}} cos\,\theta/2\,cos\,3\theta/2 * sin\,3\theta/2 \ldots \quad \textit{Equation 18}$$

$$\sigma_{zz} = \nu(\sigma_{xx} + \sigma_{yy}),\, \tau_{xz} = \tau_{yz} = 0 \ldots \quad \textit{Equation 19}$$

And the displacement fields are:

$$u = \frac{K_I}{G}\sqrt{\frac{r}{2\pi}} cos\,\theta/2(1 - 2\ \nu + (sin^2\,\theta/2) \ldots \quad \textit{Equation 20}$$

$$v = \frac{K_I}{G}\sqrt{\frac{r}{2\pi}} sin\,\theta/2(2 - 2\ \nu - cos^2\theta/2) \ldots \quad \textit{Equation 21}$$

$$w = 0 \ldots \quad \textit{Equation 22}$$

3.3. Fracture toughness test standards

Fracture toughness testing and evaluation of bio-composites has been a very important subject in the development of fracture mechanics. Therefore in order to investigate the fracture toughness of such materials experimentally we can use the fracture toughness test standards of ASTM. ASTM D 5045-99 and ASTM standard compact tension sample [ASTM E 399-90] are used as standard test methods for plan-strain fracture toughness and strain energy release rate for plastic and composite materials. These test methods are designed to characterize the toughness of plastic and composite materials in terms of the critical-stress intensity factor, K_{IC} and the energy per unit area of crack surface or critical strain energy release rate, G_{IC}, at fracture initiation and propagation. And also these test method is known as compact tension (CT).

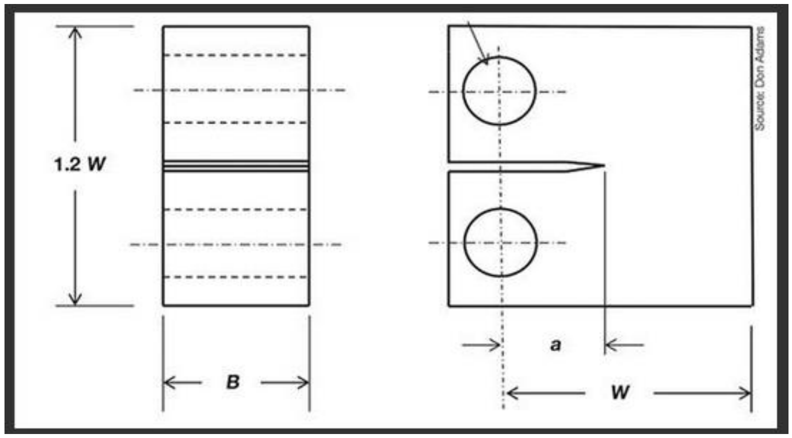


Figure 11 specimen configuration for Compact tension specimen in test method ASTM D5045-99

In this test method stress intensity factor K_I is calculated from the following espression:

$$K_I = \left(\frac{P}{BW^{\frac{1}{2}}}\right) f(x) \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots .. \text{Equation 23}$$

Where $x = \frac{a}{w}$ and it is range from 0.2 to 0.4 (0.2<x>0.4)

$$f(x) = \frac{(2+x)(0.886+4.64x-13.32x^2+14.72x^3-5.6x^4)}{(1-x)^{3/2}} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots .. \text{Equation 24}$$

Where: P = load, B = specimen thickness , W = specimen depth (width) and a = crack length

In this thesis work compact tension specimen is used to investigate critical stress intensity factor, K_{IC}, for mode one fracture of sisal fiber reinforced composite material and the test sample has been prepared with standard dimension stated by ASTM D 5045-99.

3.4 Finite Element

The finite element (FEA) method essentially solves the basic spring equation for segmented regions of a larger body. Then secondary quantities such as strain and stress are derived from approximation functions and basic constitutive relations. This method is an approximation that generally provides improved results as the number of regions or elements used to represent a body is increased. This is increased subdivision is called mesh refinement.

The role of finite element analysis is potentially unlimited. Finite element simulations are generally used to model experimental phenomena. In the case of costly experiments with limited material and facilities, finite element simulations can reduce the number of iterations required to perfect experimental procedures. The primary function of FEA is modeling complex geometries that cannot easily be tested or represented by simpler methods. And to model the compact tension test sample ABAQUS 6.13 has been used and strain energy release rate as well as stress intensity factor has been evaluated using this program.

3.4.1 Strain Energy Release Rate

The strain energy release rate (or simply energy release rate) is the energy dissipated during fracture per unit of newly created fracture surface area. This quantity is central to fracture mechanics because the energy that must be supplied to a crack tip for it to grow must be balanced by the amount of energy dissipated due to the formation of new surfaces and other dissipative processes such as plasticity.

For the purposes of calculation, the energy release rate is defined as

$$G = \frac{(U-V)}{A} \quad \textit{Equation 25[10]}$$

Where: U is the potential energy available for crack growth

V is the work associated with any external forces acting, and

A is the crack area (crack length for two-dimensional problems). The units of G are J/m^2.

The energy release rate failure criterion states that a crack will grow when the available energy release rate G is greater than or equal to a critical value G_C

$$G \geq G_C \quad \textit{Equation 26}$$

The quantity G_C is the fracture energy and is considered to be a material property which is independent of the applied loads and the geometry of the body.

3.4.2 Relation to Fracture Toughness

For two-dimensional problems (plane stress, plane strain) involving cracks that move in a straight path, the mode I stress intensity factor (K_I) is related to the energy release rate (G) by

$$G = \frac{{K_I}^2}{E'} \quad \textit{Equation 27[10]}$$

Where: E' is the Young's modulus and $E' = E$ for plane stress and $E' = \frac{E}{1-u^2}$ for plane strain.

Therefore, the energy release rate failure criterion may also be expressed as

$$K_I \geq K_{IC} \quad \text{Equation 28}$$

Where: K_{IC} is the mode I fracture toughness.

Chapter Four: Materials and Methods

4.1 Materials

4.1.1 Matrix

A. EPOXY RESIN

For this master thesis work I used epoxy resin as matrix with a brand name of SYSTEM # 2000 EPOXY RESIN, which is purchased from the local fiber glass production industries in Addis Ababa, Ethiopia. Epoxy resin is one of the most exciting polymer type and which is used in advance to produce composite material with different reinforcing elements. Their extensive use is mainly due to their superior mechanical properties, excellent adhesion, good possibility utilizing addition- type reaction, low cure shrinkage and low cost.

B. Hardener

Epoxy resin is cured by adding a catalyst, which causes a chemical reaction without changing its own composition as well as property. The catalyst initiates the chemical reaction of the epoxy resin and monomer ingredient from liquid to solid state. Therefore, the hardener (curing agent) used for this specific project/research work is hardener with a brand name of SYSTEM # 2060 HARDENER, which is purchased from local market.

4.1.2 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 hand- pulled through in longitudinal direction gently, removing the resinous material as shown in the figure below. 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. This fiber is now ready for fabrication of the test specimen.

Figure 12(a) Harvesting the sisal plant (b) extraction pocess (c) the extracted fiber

4.1.3 Sodium hydroxide

Sodium hydroxide, also known as lye or caustic soda, has the molecular formula NaOH and is a highly caustic metallic base and alkali salt. Pure sodium hydroxide is a whitish solid, which is available in pellets, flakes, granules, and as a 50% saturated solution [33]. Sodium hydroxide is soluble in water, ethanol and methanol. This alkali is deliquescent and readily absorbs moisture and carbon dioxide in air. Although molten sodium hydroxide possesses properties similar to those of the other forms, its high temperature comparatively limits its applications. Sodium hydroxide is used in many industries, mostly as a strong chemical base in the manufacture of pulp and paper, textiles, drinking water, soaps and detergents [33]. In this work we used NaOH in pellets form, purchased from local suppliers with the brand name and code of RANKEM, S0290 respectively and performed chemical treatment of sisal fiber

4.2 Methods for Sample Preparation

4.2.1 Preparation of sisal fiber

In this thesis work investigation were performed to analyze the effect of fiber length on the crack propagation. Therefore the given sisal fiber has been cut into two different fiber length, fiber with 2mm fiber length and fiber with 10-15 mm fiber length, using a pair of scissors and finally the chopped fiber is obtained.

Figure 13(a) chopping the fiber *(b) the chopped sisla fiber*

4.2.2 Alkali treatment of sisal fiber

Alkali treatment is the simplest method of chemical treatment of fibers; it leads to the increase in the amount of amorphous cellulose at the expense of crystalline cellulose. The important modification occurring here is the removal of hydrogen bonding in the network structure. The following reaction takes place as a result of alkali treatment.

$$Fiber - OH + NaOH \longrightarrow Fiber\text{-}O^{-}Na^{+} + H_2O \qquad \text{Equation 29}$$

According to literature, alkali solution has a good effect on treating natural fibers.

In this study, a 10% NaOH solution was used to treat the raw sisal fiber, In order to improve the adhesion between the fibers and matrix, fibers were subjected to surface treatments. Sodium hydroxide is the most commonly used chemical for cleaning/bleaching the surface of cellulosic fibers. Chopped sisal fibers were soaked in 10wt% NaOH solution for 24 hours. The treated fibers were washed in distilled water in order to neutralize excess of NaOH. This treated sisal fibers were dried in sun light for two days before using as reinforcement in the synthesis of composite.

To perform this treatment efficiently following the following step is recommended.

Steps:

1. Wash the chopped sisal fiber with in distilled water at 80^0c for 1hrs and dry it in oven at 100^0c for 5hrs.


Figure 14. Chopped sisal fiber with in distilled water at 80^0c for 1 hrs


Figure 15. Sisal fiber dried with inside the oven and after the oven

2. The second step is sisal fiber mercerization. It is a process of treating sisal fiber after oven with 10wt% NaOH solution at room temperature for 24hrs.

Figure 16sisal fiber soaked in NaOH solution for 24hrs

3. Next rinse the fiber (sisal fiber) with water to remove the soda excess until PH ~ 7 will reach.

Figure 17. Pure sisal fiber after mercerization

4. Finally the fiber has been dried by sun light.

4.2.3 Weight fraction and volume fraction of the fiber and the matrix content of the composite

The volume of the composite has been defined by the length, width and depth of the mold, which is prepared for molding the composite material and the total volume of the composite is also the sum of the volume sisal and epoxy resin.

$$V_C = L * W * D \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \textit{Equation 30}$$

$$V_C = V_S + V_E \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \textit{Equation 31}$$

Where: $V_C$is volume of the die/ the composite, V_S *is volume of sisal and*

V_E is volume of epoxy resi, L is length of the mold,

W is width of the mold and D is depth is the mold

The density of the composite was calculated by a method enable the rule of law of mixture to be applied and was obtained first by adding the volume fracture of the epoxy resin and sisal fiber for each fiber- matrix ratio. After calculating the density of the composite material the total mass of the composite is calculated.

Density of composite

$$\rho_C = \frac{m_C}{V_C} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \textit{Equation 32}$$

Where: m_C is mass of composite

V_C is volume of composite

We can define the volume of the composite from the above density equation:

$$\frac{m_C}{\rho_C} = \frac{m_S}{\rho_S} + \frac{m_E}{\rho_E} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \textit{Equation 33}$$

Where: m_S is mass of sisal, m_E is mass of Epoxy,

ρ_S is density of sisal $= 1.33$ gm/$cm^3$and

ρ_E is density of Epoxy $= 1.2$ gm/cm^3

Mass composition of the composite is percent mass composition of the fiber plus percent mass composition of Epoxy.

$$m_C = x\% * m_S + y\% * m_E \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \textit{Equation 34}$$

Where: x% is mass fraction of sisal fiber and y% is mass fraction of Epoxy resin and x+y=1.

<u>Calculation to find the mass composition of the composite material for test sample preparation:</u>

$$volume\ of\ the\ die\ or\ composite, V_C = L * W * D \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \textit{Equation 35}$$

$$V_C = 200 * 200 * 5 = 200000\text{mm}^3 = 200\text{cm}^3$$

1. <u>For chopped fiber mass composition</u>
   For different fiber- matrix ratio the mass composite of the composite material has been summarized in the table below.

Table 1. Fiber- matrix mass composition

Designation	Composition (%)		Mass (gram)			No. of samples
	Epoxy	Sisal fiber	Sisal	Epoxy	Total	
ST (F) 15	85	15	36.6	207.4	244	3
ST (F) 20	80	20	48.78	195.12	243.9	3
ST (F) 25	75	25	61.5	184.5	246	3
ST (F) 30	70	30	74.17	173.08	247.25	3
ST (F) 40	60	40	99.9	149.86	249.76	3

4.2.4 Preparing the sample

Preparation of epoxy and hardener:

Epoxy of SYSTEM #2000, mixed with hardener SYSTEM #2060 is used to prepare the composite plate. The weight ratio for mixing epoxy and hardener is 10:1. Hardeners include anhydrides (acids), amines, polyamides, dicyandiamide etc. The mixer is strewed with stirrer for about one minutes continuously The mixing is performed in the mixing containers(Bowl) the bowl is made of Nickel to prevent melting of the Bowl during the exothermic reaction with the tongue depressor the mix is done slowly so as to not entrain any excess air bubbles in the resin.

Hand Lay-Up:

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. The quantity of accelerator and catalyst added to resin at room temperature for curing was 1% by volume of resin each. Fiber deformation and movement should be minimized to yield good quality, random fiber composites. Therefore, at the time of curing a compression pressure of 50 bar (5MPa) was applied on the mold and the air gaps formed b/n the fibers during the processing were gently squeezed out by hydraulic press to force the air present in between the fibers and resin, and kept several hours to get the perfect samples the processed wet composite were then pressed hard and the excess resin is removed and dried. Fiber configuration and volume fraction are two of the most important factors that affect the properties of the composite.

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

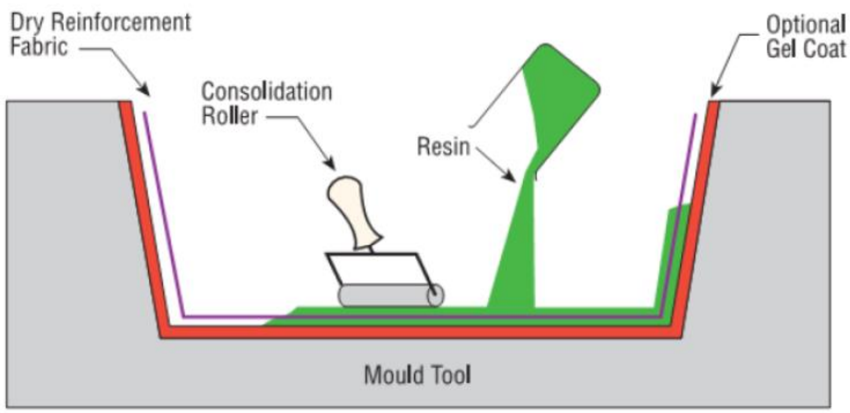


Figure 18 Hand-lay-up method

Materials Requirements of Hand-lay-up method

- Mold
- Roller
- Mold release

I. Mold preparation

The pattern is made up of sheet metal with 300*250*20mm and it contains the basic parts, such as base plate, cover frame and mold releaser. 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 the curing time.

Figure 19 *(a)Mold plate* *(b) mold plate with cover frame*

II. **Mold Release**

Mold release is essential for preventing the epoxy from sticking to the mold when the composite 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

<u>during sample preparation</u>

First of all 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 below. We press the mold on press machine for consolidation and this sample is then left for 3-5hours. 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 carefully plastics are removed from the steel mold. Eventually the required composite material produced.

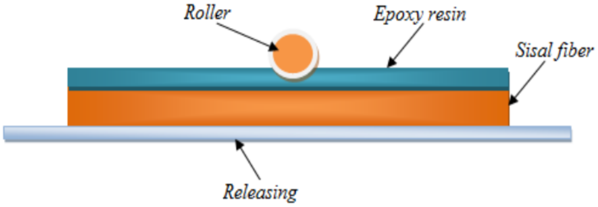


Figure 20. Sisal fiber reinforced epoxy composite molding sketch map

Figure 21. Sisal fiber- epoxy resin mixture in the mold surface at AAIT lab

Compression and Curing:

5Mpa of pressure was maintained and it requires 3-5 hours for curing at room temperature. After curing period the sisal fiber polymer matrix were removed from the mold. A typical hydraulic press used for curing SFREC is shown in figure below.

Figure 22. Standard Hydraulic Press for curing

<u>Prepared sample</u>

Now here, choppped sisal fiber reinforced epoxy resin composite material with different fiber-matrix composition is ready for test and typical view of some composite boared is show below.

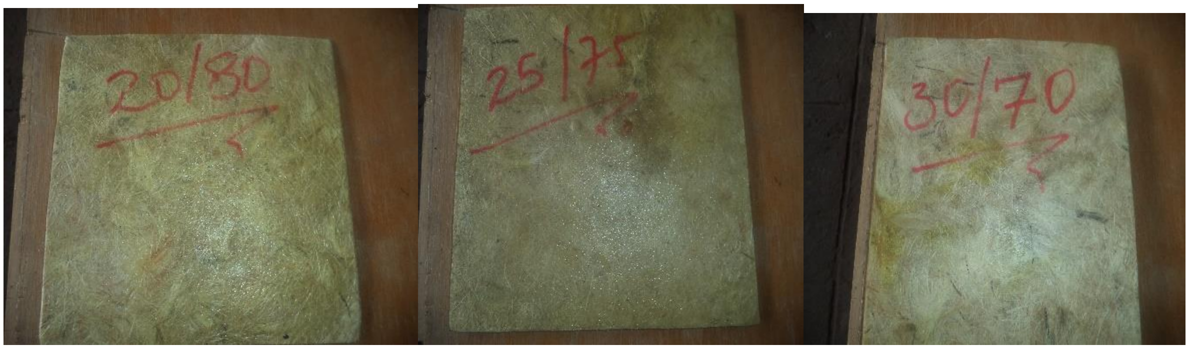


Figure 23. Prepared sample with different mass composition

4.3 Experimental Procedures and steps

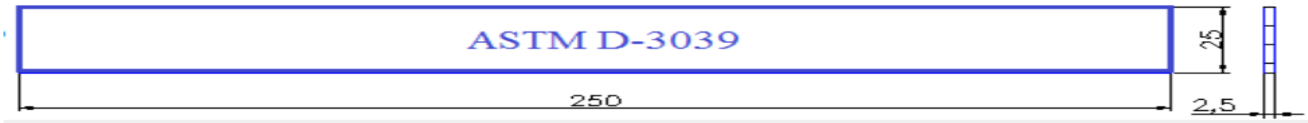
In order to evaluate the fracture toughness parameter, stress intensity factor, of the chopped sisal fiber reinforced epoxy resin composite material, compact tension specimen sample have been developed using ASTM standard, ASTM D 5045-99 (ASTM E 399-90). And tensile test has been performed for the sake of young’s modules evaluation, which is important parameter and material property for the modeling of compact tension specimen in ABAQUS 6.13 software. It has been evaluated from engineering stress-engineering strain curve.

The fracture toughness tests (compact tension test) in this paper work needs a total of 15 test sample specimen and 3 tensile test specimen for 30/70% fiber-matrix composition also prepared for the young’s modules investigation. Test specimens were prepared with appropriate dimension using band saw as shown in the figure 24.

Figure 24. Sample preparation using band saw

4.3.1 Dimension for Test Specimen

a) The appropriate American Society of Testing Materials (ASTM) standard, ASTM D-3039, was followed while preparing the tensile test specimens for Sisal fiber reinforced epoxy composite test and these sample are illustrated in *figure 25.*

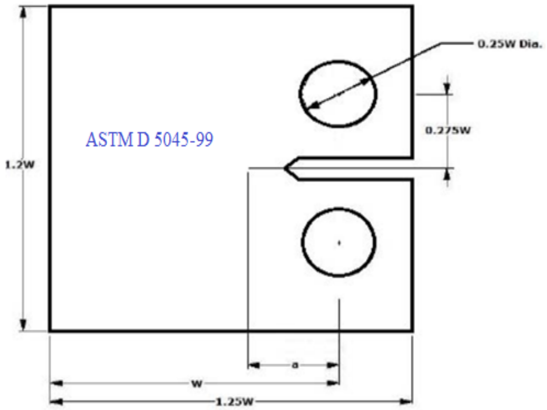


(a)

(b)

Figure 25. (a) ASTM D-3039 Standard for tensile test sample, (b) Tensile test sample prepared in AAIT lab

b) The appropriate American Society of Testing Materials (ASTM) standard ASTM D 5045-99 was followed while preparing the compact tension test specimens for 5 different fiber-matrix composition of Sisal fiber reinforced epoxy composite test and these samples are illustrated in figure 26.



(a) (b)

Figure 26. (a) ASTM D 50 45-99 standard for Compact tension specimen used for mode I fracture toughness test, (b) Compact tension specimen prepared in AAIT lab.

After the chopped Sisal fiber reinforced epoxy composite Specimen cut in to 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 test and tensile strength test for 30/70% have been performed using UTM machine.

4.3.1.1 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 *figures 27.* 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.

Figure 27. Universal testing machine testing system working sketch map

Figure 28 Universal testing machine in AAIT work shop

4.3.1.2 Tensile Strength Test (ASTM D3039/D3039M):

The primary objective of this test was to evaluate the in-plane tensile properties of chopped sisal fiber composites. For 30/70% sample, 3 specimens were tested in UTM machine. Each specimen was 25*2.5* 250 mm. During the test the specimens were placed in the grips of UTM and axial load is applied through both the ends of the specimen. Typical points of interest when testing a material include: ultimate tensile strength (UTS) or peak stress; The cross-head speed used was 0.5 mm/min, and gauge length was 200 mm. Load and elongation were acquired in real time by machine and provided at the end of each test. Typical specimen under tensile strength test is shown in *figure 29.*

Figure 29. Typical specimen under tensile strength test

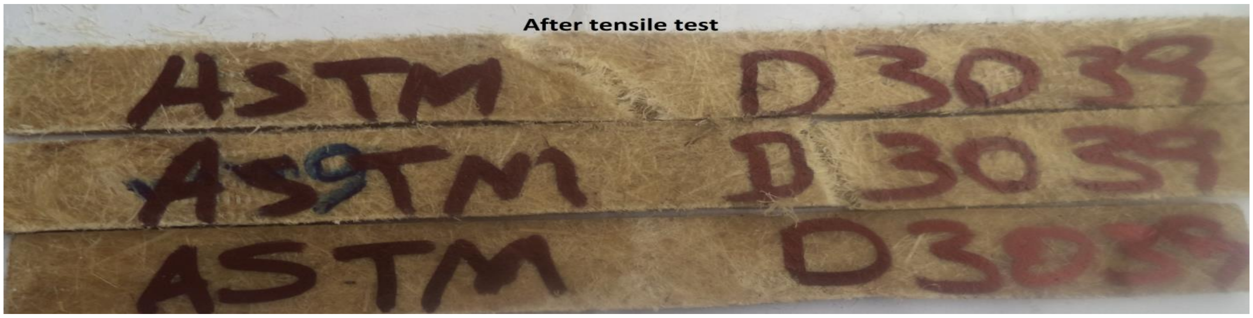


Figure 30. Sisal fiber reinforced epoxy composite material after Tensile Test

4.3.2 Fracture Toughness Test for Mode one Fracture using Compact tension test (ASTM D 5045-99)

Here compact tension sample was prepared for 0.3 ratio value between crack length, 'a' and crack width, 'w' ($\frac{a}{w} = 0.3$). For each sample, 3 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 me in AAIT work shop. The cross head speed used was 0.5mm/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 the figure 31 (a).

(a)

(b)

Figure 31. (a) Typical CT specimen under compact tension test under UTM machine in AAIT lab (b) Sisal fiber reinforced epoxy composite material after compact tension test

4.4 Fracture Toughness Investigation Using Finite Element Method

This section describes the modeling approach methodology that was followed in this project, the finite element method. In order to verify that the model approach would be valid, the known and widely used compact tension specimen was modeled first and the results were compared with the result which is obtained from experiment. Compact tension specimen model for 30/70 mass composition on ABAQUS 6.13 were prepared. Details of results can be found in the next chapter.

4.4.1 CT Specimen in ABAQUS 6.13

The 2D model of the compact tension specimen for the chopped sisal fiber epoxy resin composite material has been modeled in ABAQUS 6.13 software.

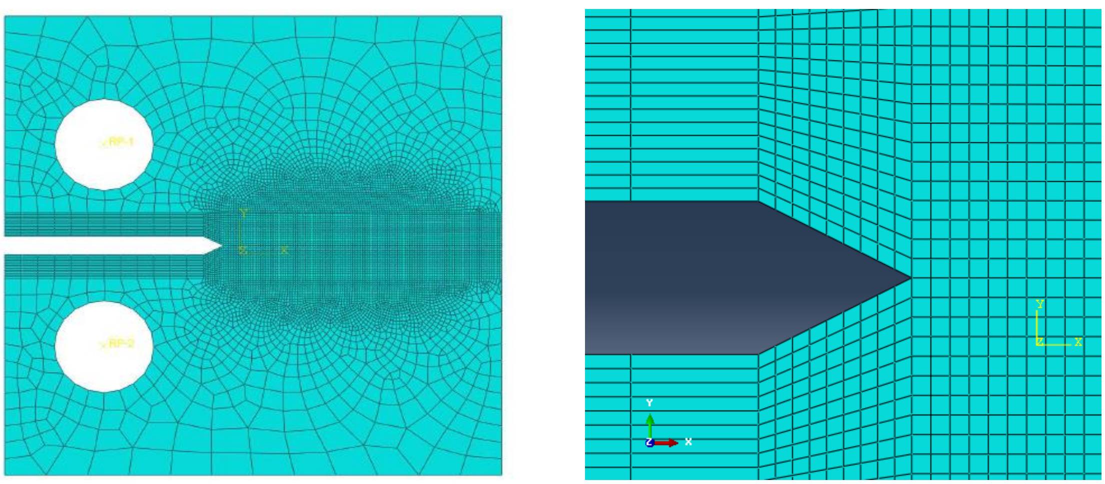


Figure 32.Compact tension specimen after fine mesh

4.4.2Analysis procedure

The first step of the analysis was to perform finite element elastic stress analysis on the un cracked compact tension specimen to determine the stress distribution across the stress concentration area (notched surface) and identify the weakest point or high stress regions. The finite element model of the un cracked compact tension specimen had 8369 elements and 8423 nodes. After applying the boundary conditions to the model as shown in the figure 33, the single load step static stress analysis were performed. Once the calculation was completed, the ABAQUS POSTPROCESSOR was used to identify the high stress region for introduction of the initial crack. Finally the ABAQUS wrote a database DB file (odb), which was subsequently used as input for crack growth analysis

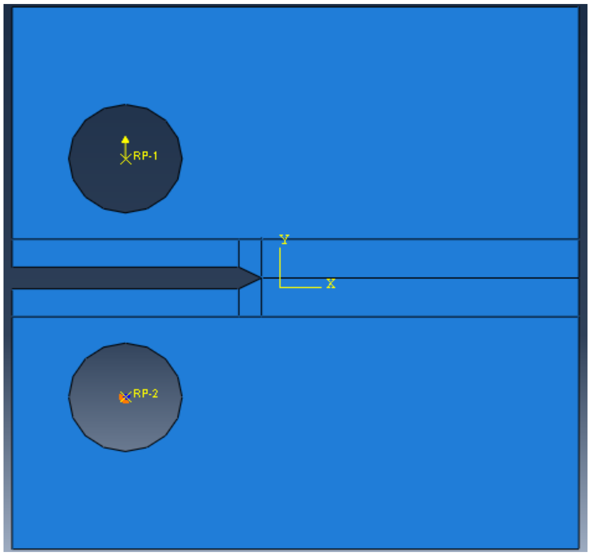


Figure 33. The boundary conditions for un cracked CT sample.

The next step of the analysis was the analysis of the crack growth and investigation of the stress intensity factor for the compact tension specimen for the ratio of crack length and crack width, which is equals to 0.3, at different loading condition until the maximum load which was calculated form experiment. And for every loading condition ALL STRAIN ENERGY has been collected for the given model for both cracked and un cracked conditions.

In the final step the corresponding strain energy release rates are computed from ALL STRAIN ENERGY, eventually the stress intensity factors are calculated based on the results.

Chapter 5- Result and Discussion

5.1 Experimental Result

5.1.1 Tensile Test

For tensile strength evaluation, there were three specimen for fiber/matrix ratio (30/70%) treated SFREC, while the typical Engineering stress - Engineering strain curve of sisal fiber reinforced epoxy composite (SFREC) under tensile loading for typical ratio of sisal/epoxy resin composite specimen is presented in *figure 34.* The initial relatively steep part of the curve represents elastic behavior and the slope of the curve defines the elastic modulus. Using a sharp pencil and a ruler, by carefully draw a straight line through as much of the straight portion of the curve as possible, extending it from the bottom of the chart. This straight line is referred to as the **Modulus Line**, from which the **Modulus of Elasticity** will be calculated for the material tested.

The modulus of elasticity (Young's Modulus) is the ratio of stress in Mpa to strain in millimeters per millimeter (mm/mm.) as computed from the modulus line.

$$E = \frac{\sigma}{\varepsilon} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \text{Equation 36}$$

Where: E is young's modulus in Gpa, σ *is engineering stress and* ε *is engineering strain*

To find the modulus, by taking any two points on the modulus line, and divide the differential between their stress values in Mpa from the strain differential in mm/mm.

Therefore the maximum tensile strength and tensile modulus of the 30/70 wt% of chopped sisal fiber – epoxy matrix composite material are 50.8 Mpa and 2.19 Gpa respectively.

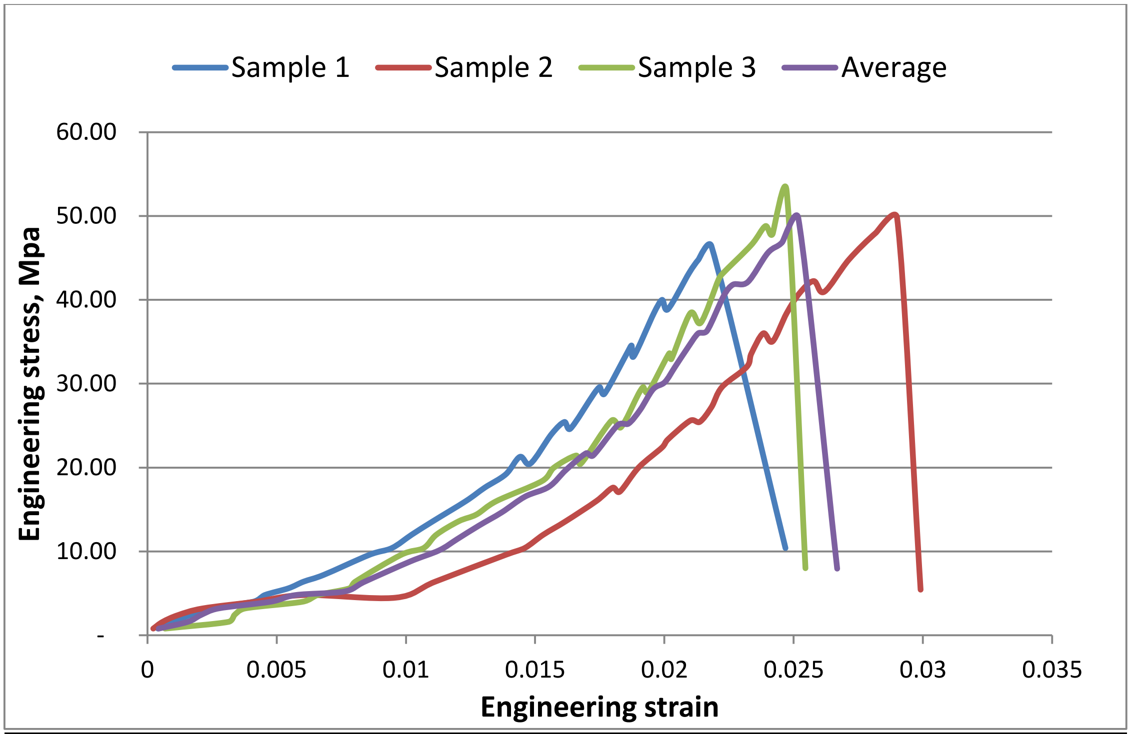
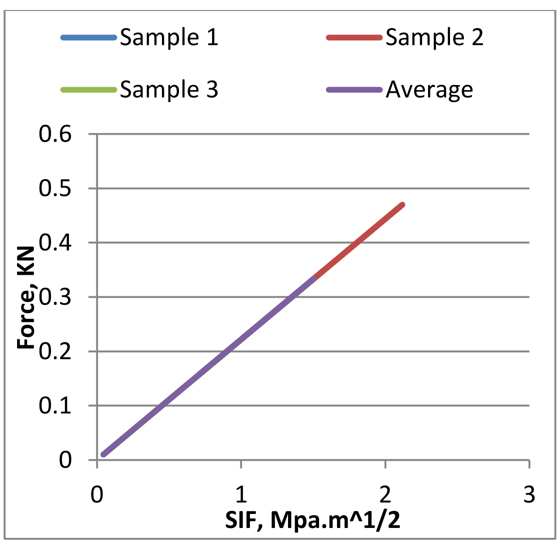


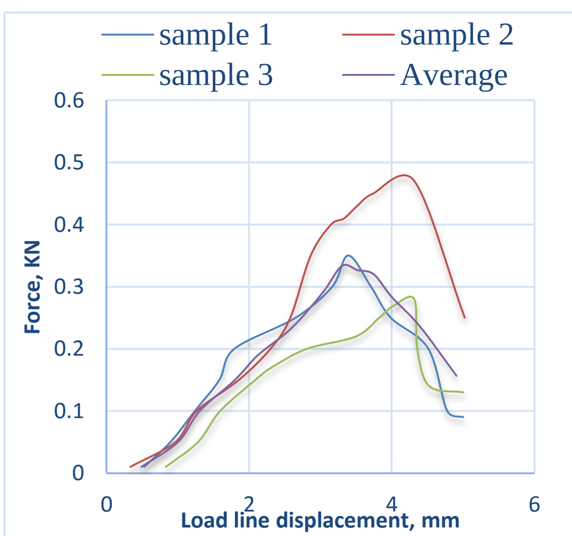
Figure 34. Engineering stress- Engineering strain curve for 30/70% fiber- matrix composition

5.1.2 Compact Tension Test Result

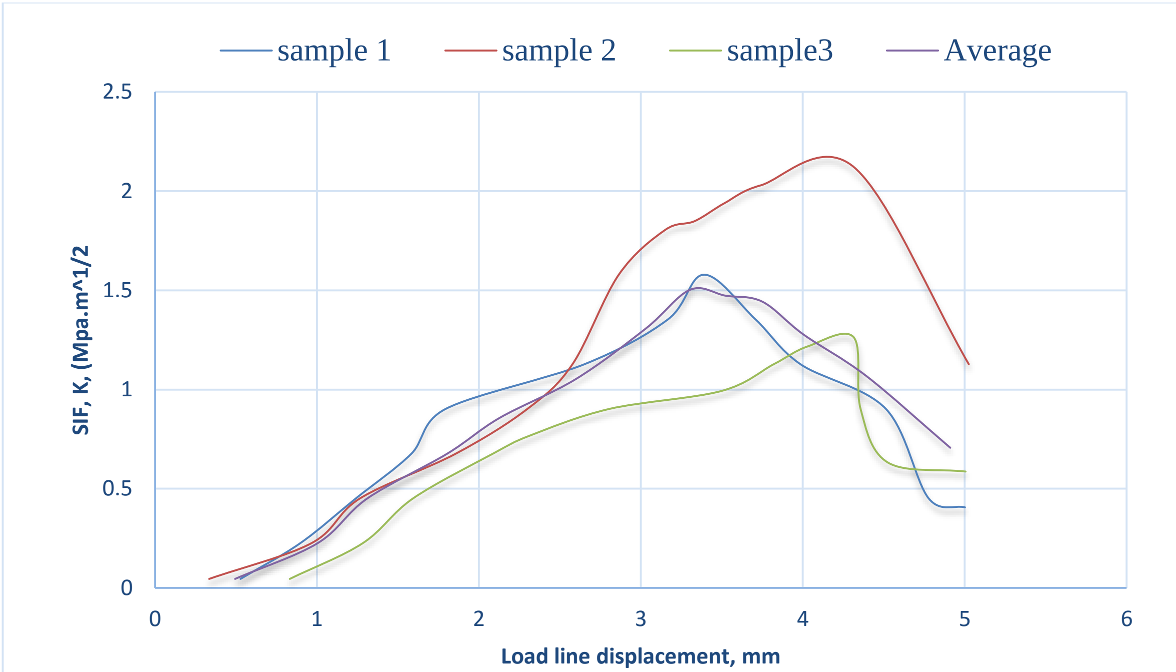
Three (3) test samples were prepared for each mass composition of fiber and matrix for Compact Tension test. And experimental result of these specific tests have been summarized using graphs, which can relate different material properties that are used in fracture mechanics to show fracture resistant of a given composite material, including stress intensity factors (SIF).



(a)

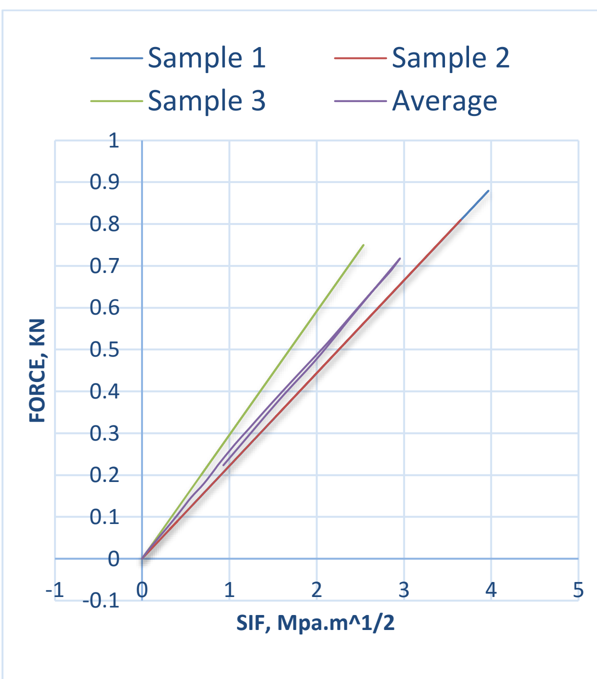


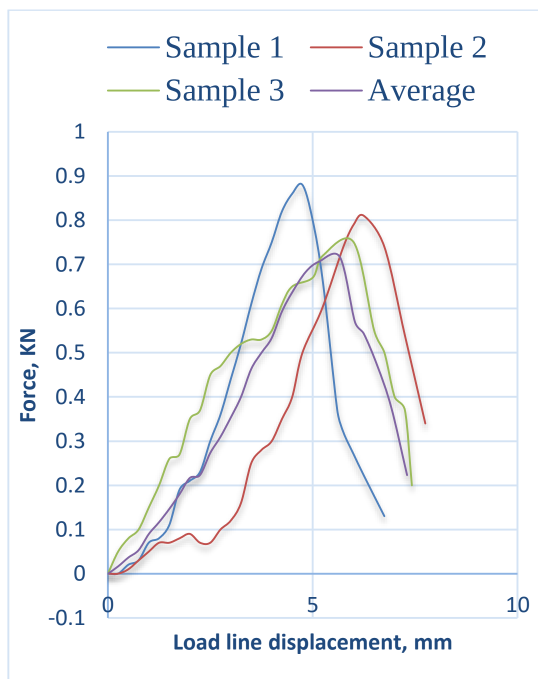
(b)



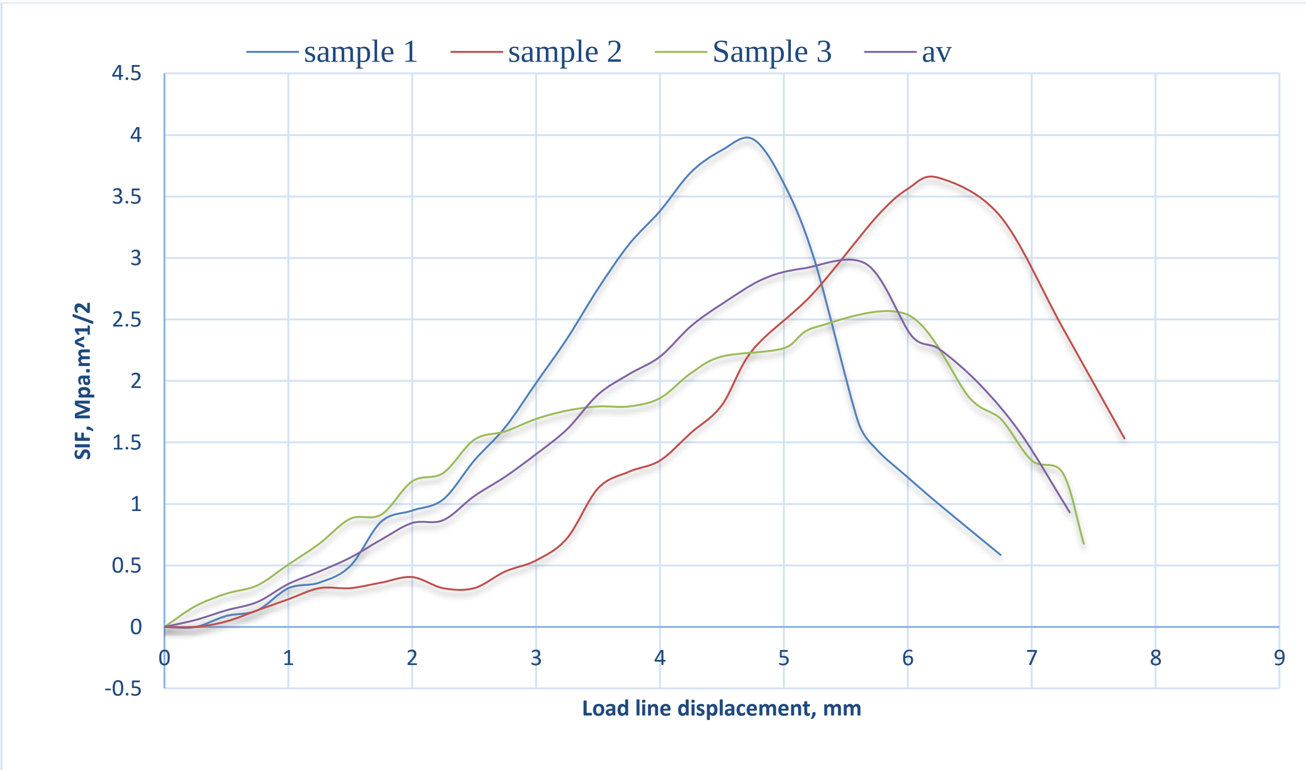
(c)

Figure 35. Compact Tension Test result for 15/85% mass composition, (a) force Vs stress intensity factor, (b) force Vs Load line displacement and (c) stress intensity factor Vs Load line displacement



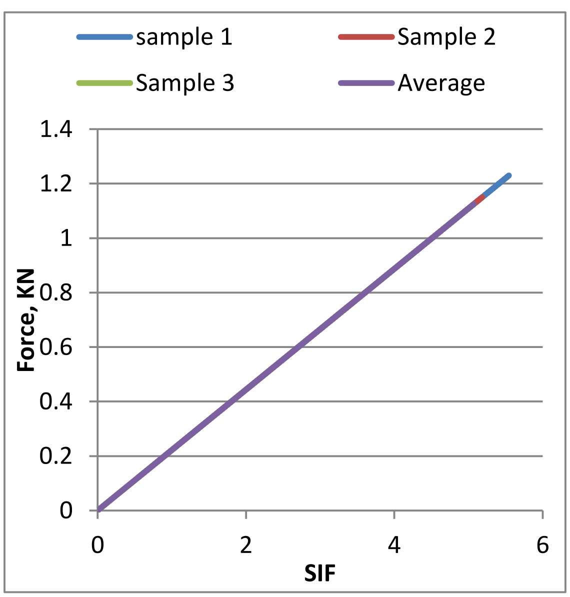


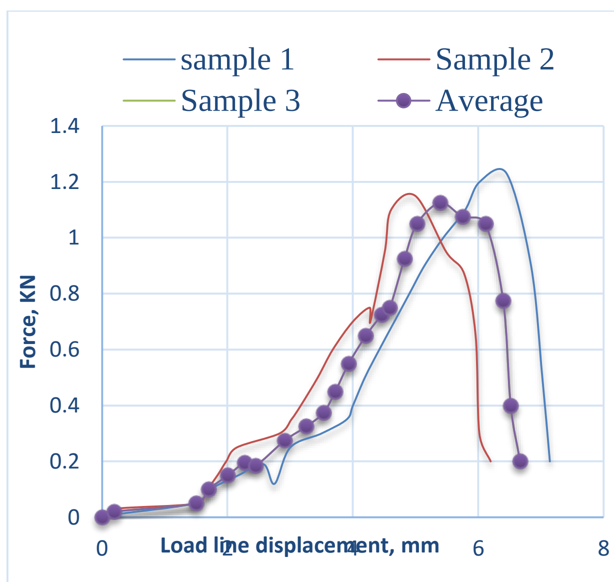
(a) (b)



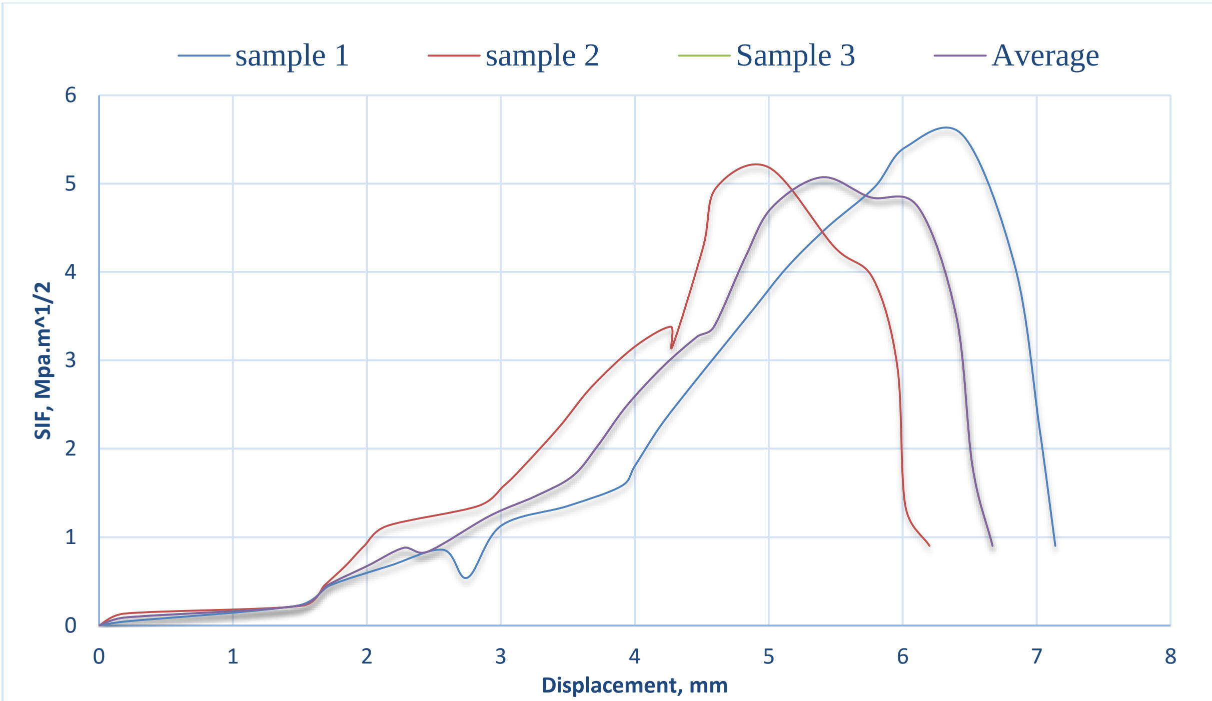
(c)

Figure 36 Compact Tension Test result for 25/75% mass composition, (a) force Vs stress intensity factor, (b) force Vs Load line displacement and (c) stress intensity factor Vs Load line displacement



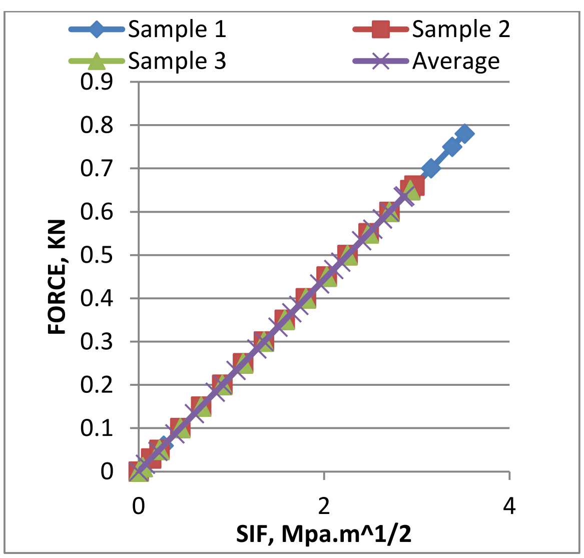


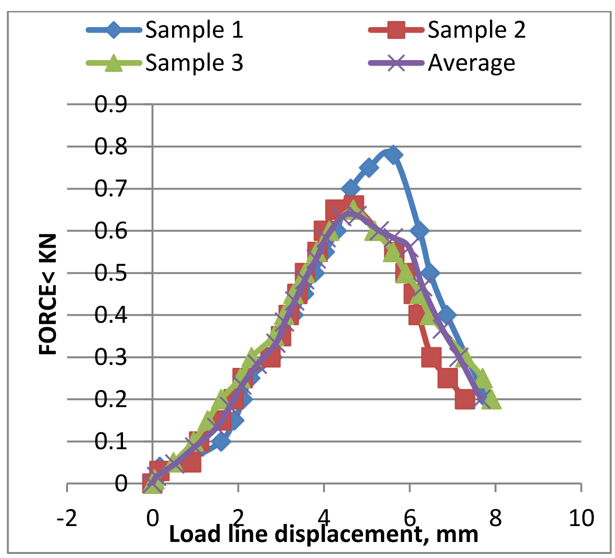
(a) (b)



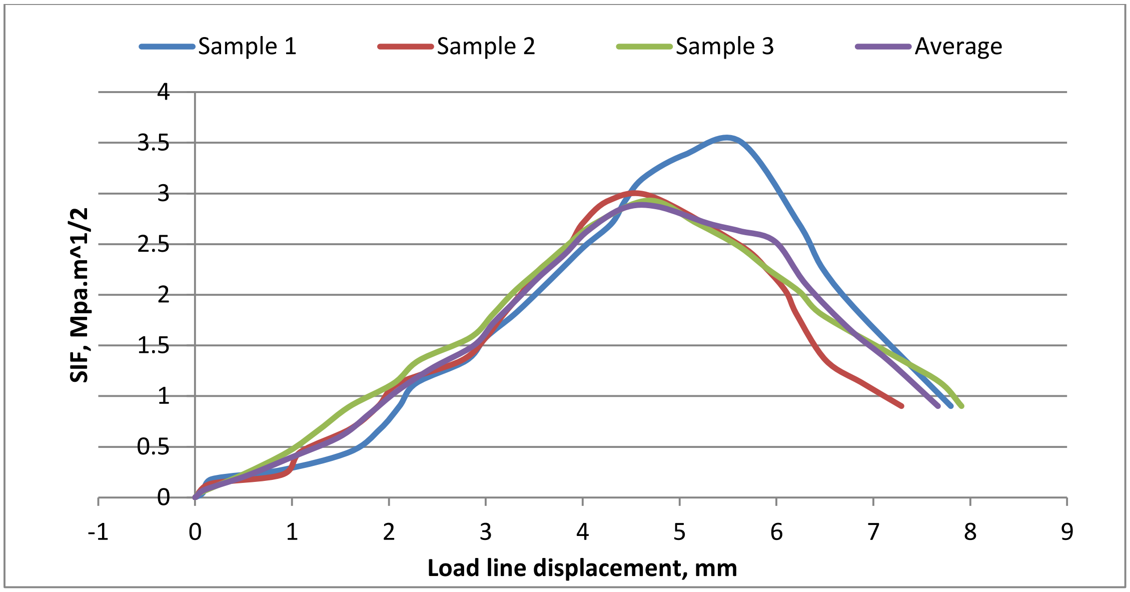
(c)

Figure 37 Compact Tension Test result for 30/70% mass composition, (a) force Vs stress intensity factor, (b) force Vs Load line displacement and (c) stress intensity factor Vs Load line displacement



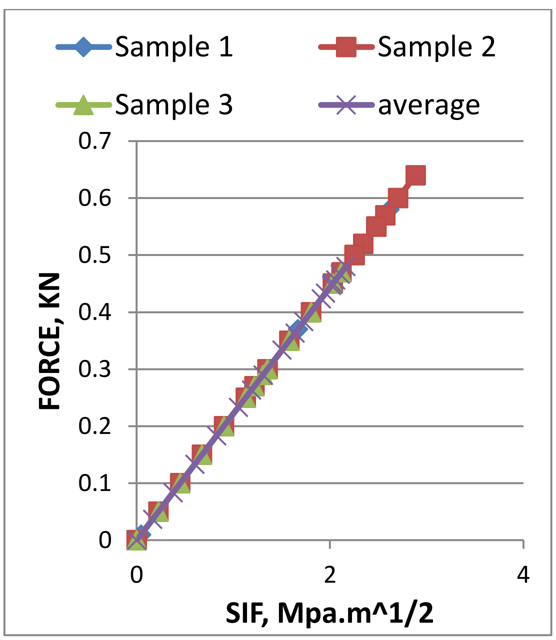


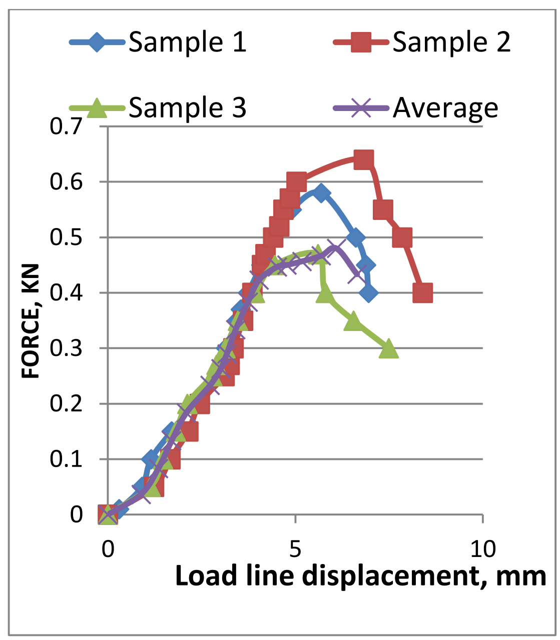
(a) (b)



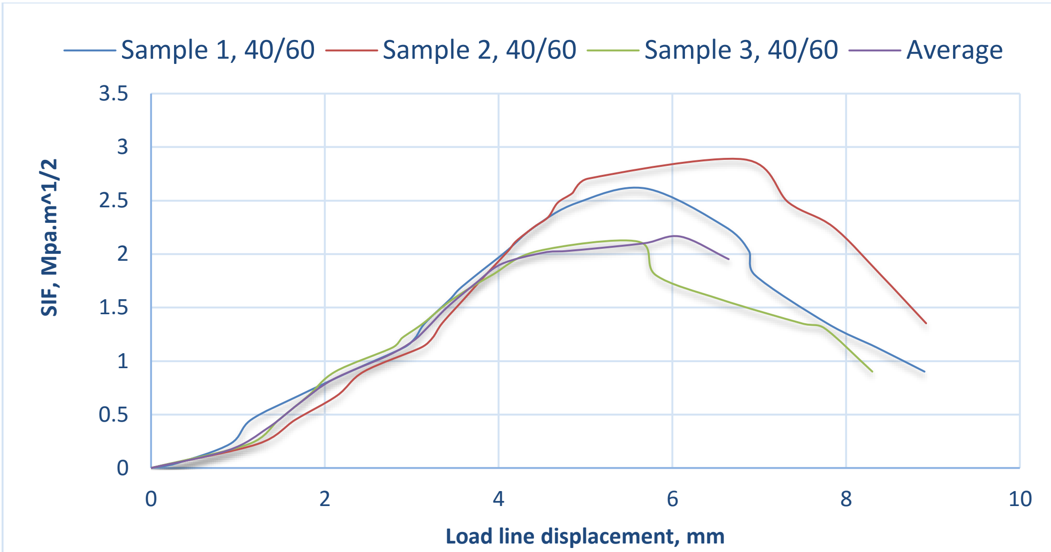
(c)

Figure 38. Compact Tension Test result for 35/65% mass composition, (a) force Vs stress intensity factor, (b) force Vs Load line displacement and (c) stress intensity factor Vs Load line displacement





(a) (b)



(c)

Figure 39. Compact Tension Test result for 40/60% mass composition, (a) force Vs stress intensity factor, (b) force Vs Load line displacement and (c) stress intensity factor Vs Load line displacement

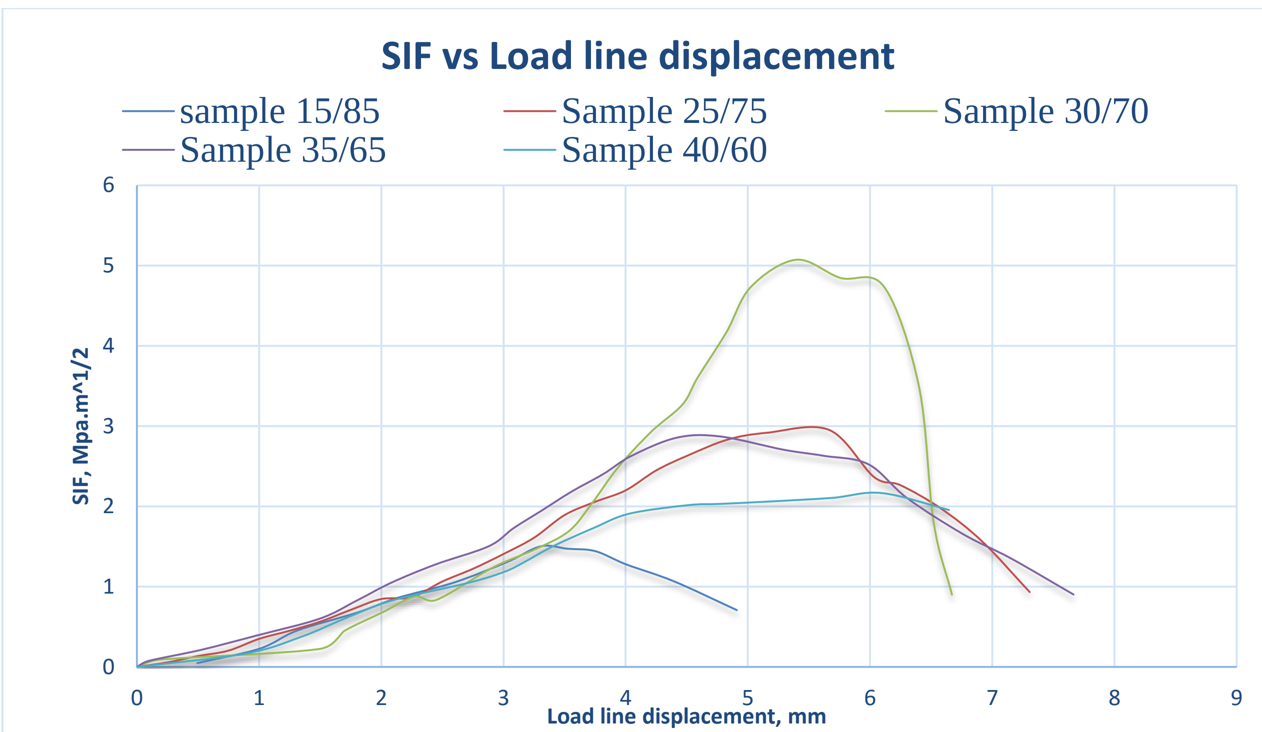


Figure 40. Compact Tension Test result for different mass composition, stress intensity factor Vs Load line displacement

5.2 Result from ABAQUS 6.13 for 30/70% Mass Composition

Fracture toughness analysis using FEM (ABAQUS 6.13) were performed for chopped sisal fiber reinforced epoxy composite with 30/70% fiber-matrix composition and the result has been summarized as follows.

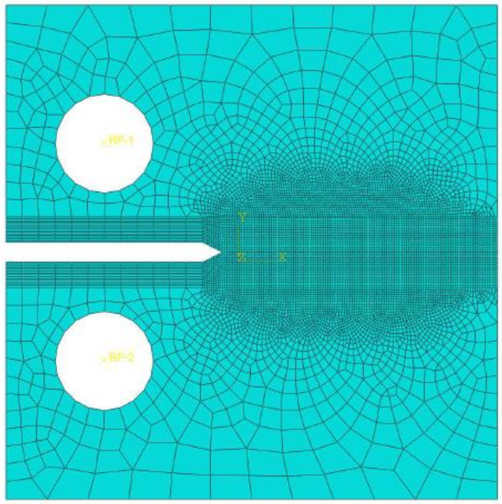


Figure 41.Meshed Compact tension specimen

5.2.1 Stress field around initial crack (zero crack length, a= 0)

For zero initial crack of compact tension specimen the computed von-mises stress field surrounding the initial crack at the maximum load is shown in the figure 40.

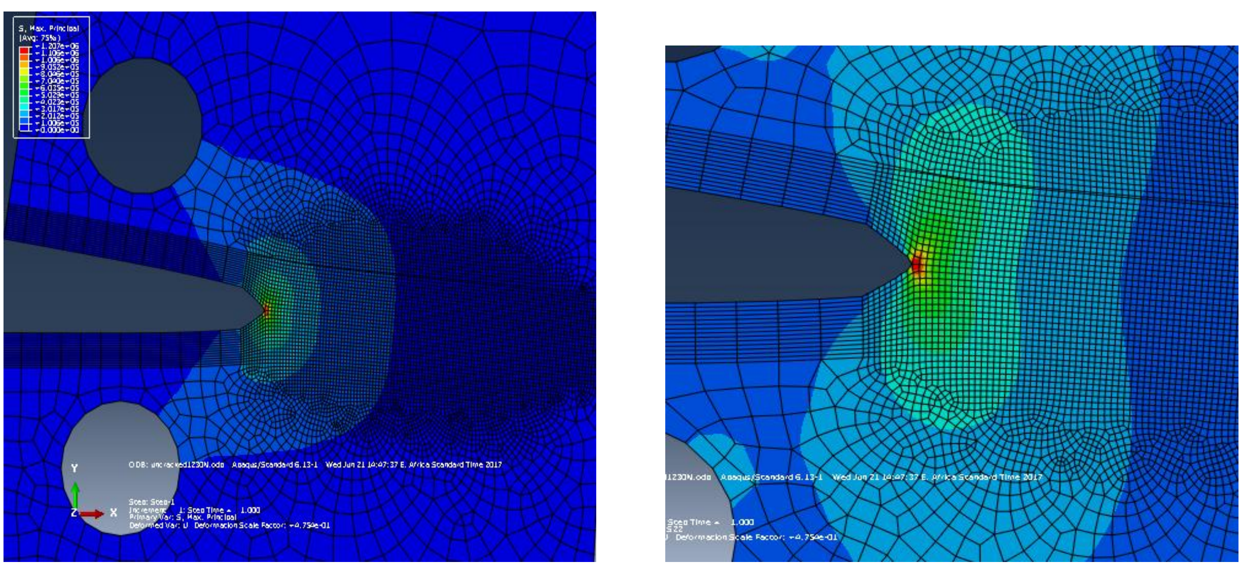


Figure 42. Stress field around initial crack (zero crack length, a= 0)

5.2.2 Stress Field around Propagated Crack (With Crack Length, A= 12mm)

Figure (41) show stress field around the propagated crack and von- misses stress field surrounding this propagated crack at the maximum load.

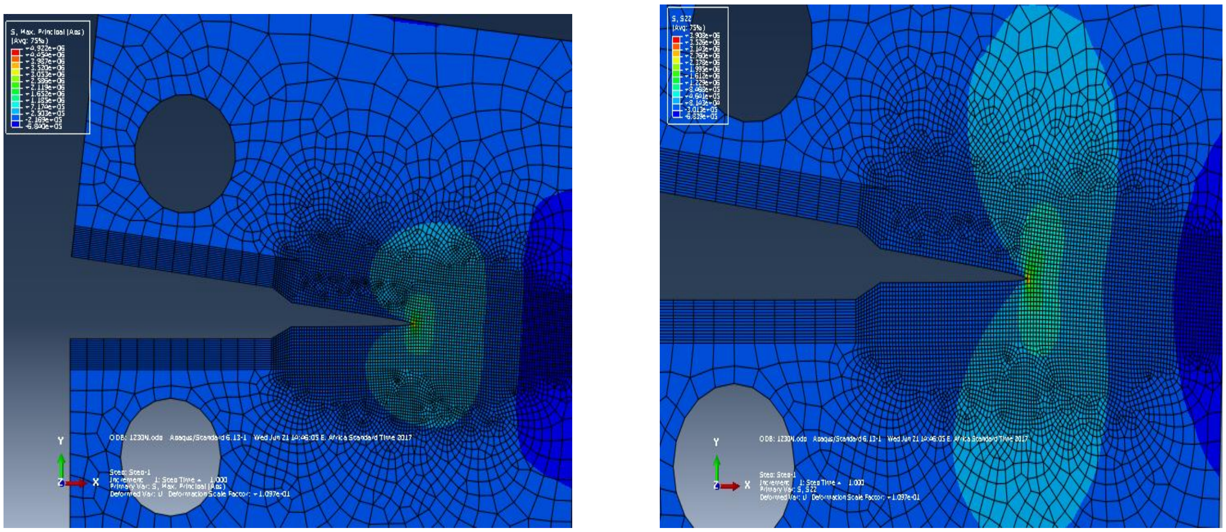


Figure 43. Stress field around propagated crack (with crack length, a= 12mm)

5.2.3 Strain Energy Release Rate (G) and Stress Intensity Factor (K_I) For Mode I Fracture

From the FEM analysis on ABAQUS, results are expressed in the context of strain energy release rate and stress intensity factor K_I for mode 1 fracture as summarized in the table.

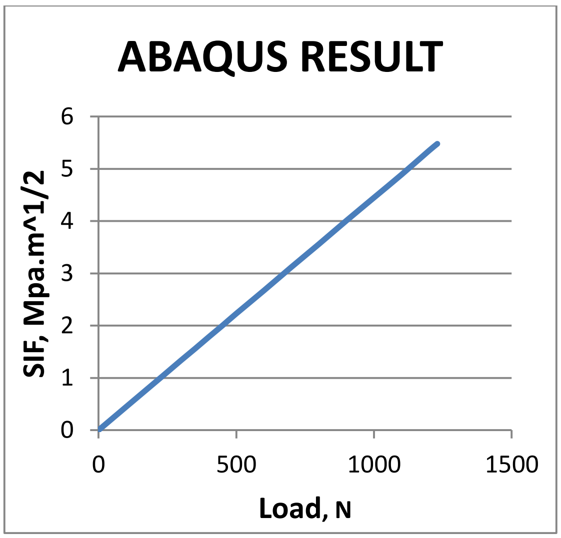
Table 2. Result from ABAQUS

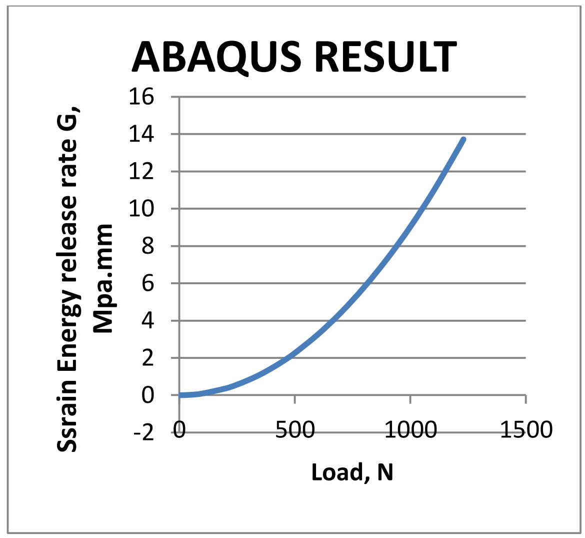
Load, N	ALLSE, 12mm CRACK, Pa.mm^2	ALLSE, 0mm CRACK, Pa.mm^2	G, Mpa.mm	SIF, Mpa.m^1/2	SIF, Mpa.mm^1/2	K/KIC	G/GIC
0	0	0	0	0	0	0	0
10	13735.8	2870.36	9.05E-04	0.0445	1.40812	0.00812	6.6E-05
50	343394	71759	2.26E-02	0.22247	7.03519	0.040597	0.001647
100	1373580	287036	9.05E-02	0.4453	14.08	0.081259	0.006599
200	5494310	1148140	3.62E-01	0.8906	28.16	0.162518	0.026385
250	8584860	1793970	5.66E-01	1.11325	35.204	0.203148	0.041247
300	12362200	2583320	8.18E-01	1.3385	4.23E+01	0.244252	0.059621
350	16826300	3516190	1.11E+00	1.557	4.92E+01	0.284124	0.080678
400	21977200	4592570	1.45E+00	1.7824	5.64E+01	0.325255	0.105758
450	27814900	5812480	1.83E+00	2.003	6.33E+01	0.365511	0.133528
500	34339400	7175900	2.26E+00	2.23	7.04E+01	0.406934	0.164723
600	49448800	10333300	3.26E+00	2.67E+00	8.45E+01	0.487226	0.237464
700	67305300	14064800	4.43E+00	3.12E+00	9.85E+01	0.569343	0.323105
800	87909000	18370300	5.79E+00	3.56E+00	1.13E+02	0.649635	0.422012

900	1.11E+08	23249900	7.32E+00	4.01E+00	1.27E+02	0.731752	0.533528
1000	1.37E+08	28703600	9.03E+00	4.45E+00	1.41E+02	0.812044	0.658163
Fro	1.66E+08	34731300	1.09E+01	4.89E+00	1.55E+02	0.892336	0.797376
1200	1.98E+08	41333200	1.31E+01	5.35E+00	1.69E+02	0.976277	0.951895
1230	2.08E+08	43425700	13.72	5.48	1.73E+02	1	1

Form the analysis critical Stress intensity factor (K_{IC}) for the chopped sisal fiber reinforced epoxy composite material is equal to 5.48 Mpa.m^1/2 (1.73E+02 Mpa.mm^1/2) and critical strain energy (G_{IC}) is equal to 13.72 Mpa.mm.

The above result is summarize using the figure 42 show below.





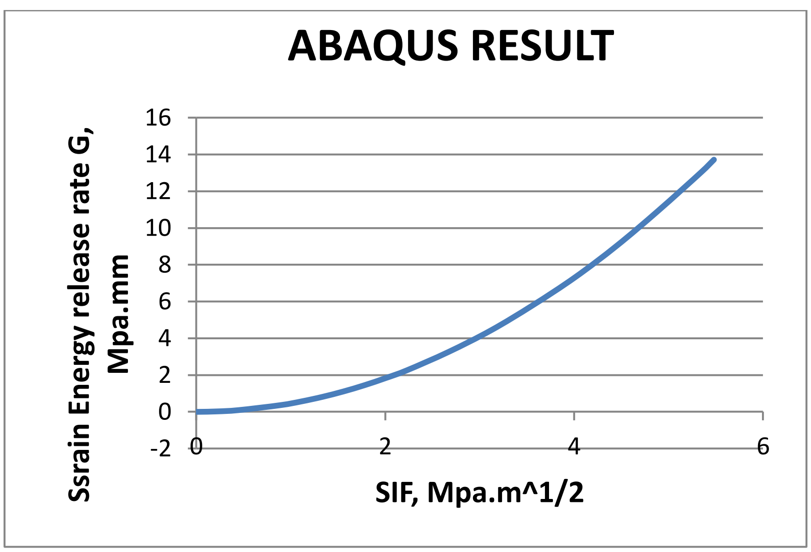


Figure 44. Result from ABAQUS for compact tension test specimen for 30/70% fiber- matrix composition

5.3 Discussion

As clearly observed from the experimental analysis, the 30/70 weight percent composition of chopped sisal fiber epoxy composite material has the best fracture characteristics as its stress intensity factor implies. The summarized critical intensity factors for different mass compositions of fiber matrix orientation is tabulated and compared using a chart as follows.

Table 3. 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

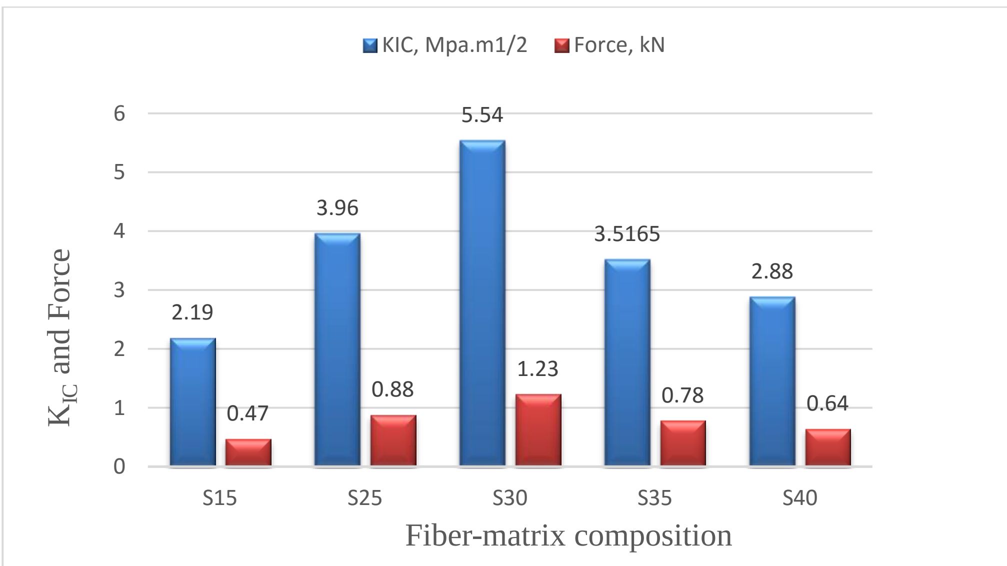


Figure 45. Experimental test result comparison for different fiber- matrix arrangement

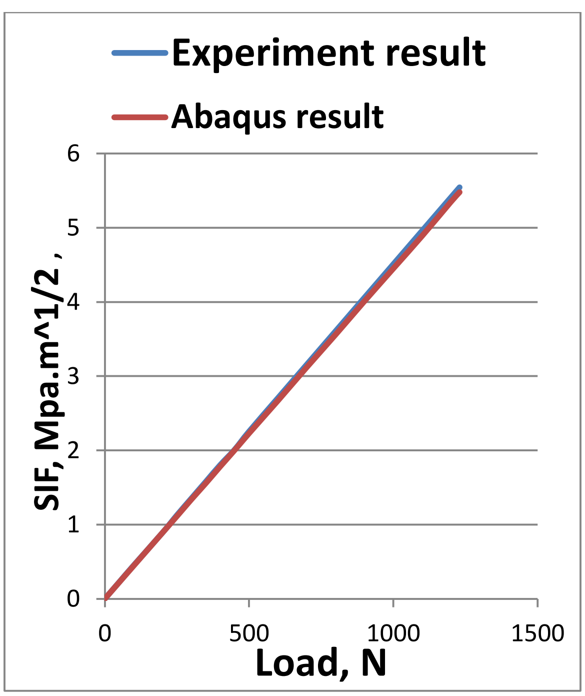
The chart proves that the stress intensity factor K_{IC} of 30/70 wt% is relatively the best. This test result is further validated using ABAQUS software.

5.3.1 Validation of Fracture toughness test (Compact Tension test) results

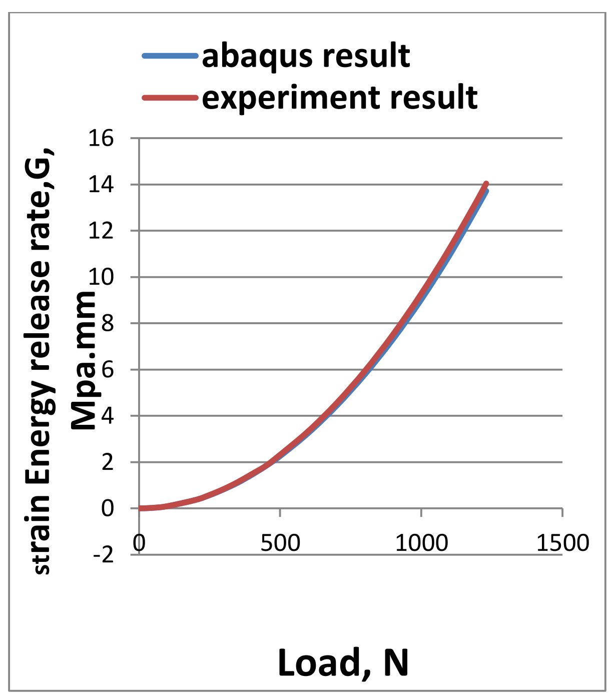
The fracture toughness test result for 30/70% mass composition of chopped sisal fiber reinforced epoxy composite has been summarized using the table (3) for both experiment and ABAQUS test. Comparison was performed between this two results and discussed using graphs that follow.

Table 4. Fracture toughness test results for both experiment and ABAQUS test

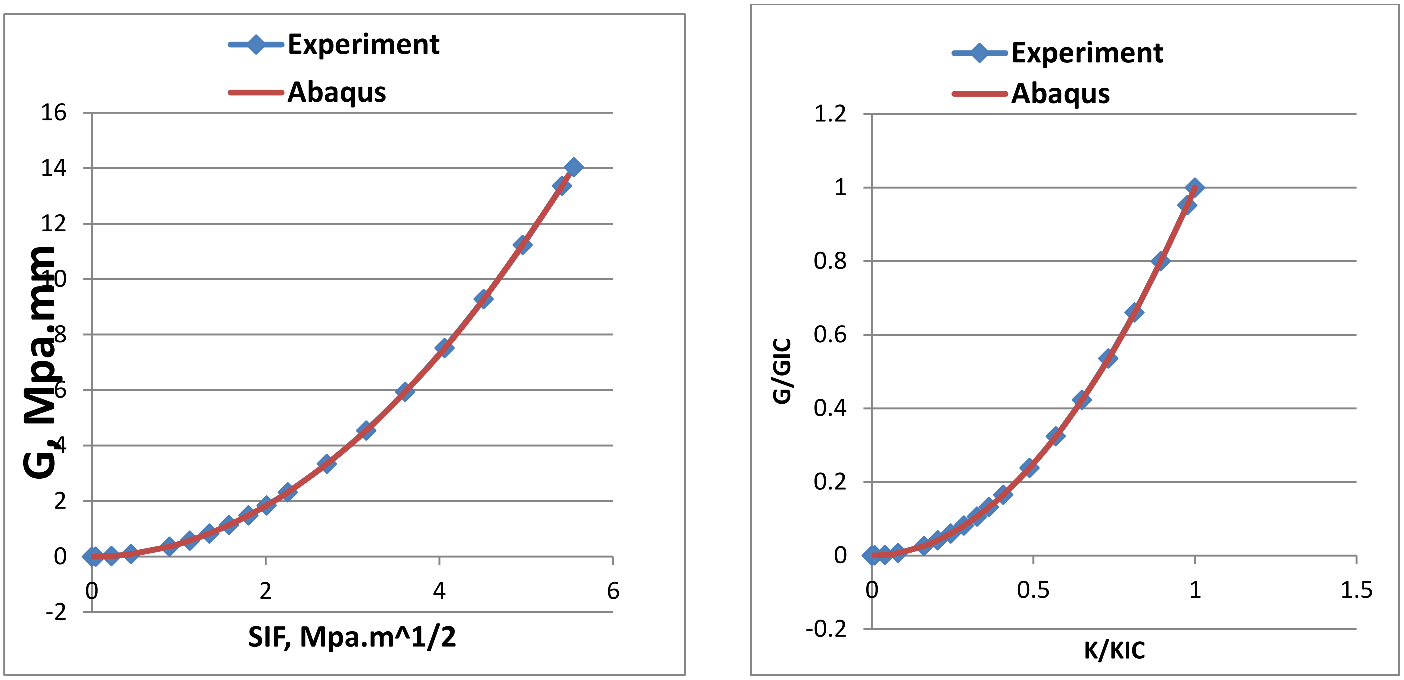
for a/w = 0.3 and 30/70% mass composition								
Load, N	G, Mpa.mm, from experiment	G, Mpa.mm from ABAQUS	SIF, Mpa.m^1/2 form experiment	SIF, Mpa.m^1/2 form ABAQUS	K/KIC form experiment	K/KIC form ABAQUS	G/GIC form experiment	G/GIC form ABAQUS
0	0	0	0	0	0	0	0	0
10	0.000928	9.05E-04	0.045083333	0.0445	0.00813008	0.00812	6.60982E-05	6.6E-05
50	0.023202	2.26E-02	0.225416667	0.22247	0.04065041	0.040597	0.001652456	0.001647
100	0.092809	9.05E-02	0.450833333	0.4453	0.08130081	0.081259	0.006609824	0.006599
200	0.362503	3.62E-01	0.891	0.8906	0.16067806	0.162518	0.025817445	0.026385
250	0.580053	5.66E-01	1.127083333	1.11325	0.20325203	0.203148	0.041311399	0.041247
300	0.835277	8.18E-01	1.3525	1.3385	0.24390244	0.244252	0.059488414	0.059621
350	1.136905	1.11E+00	1.577916667	1.557	0.28455285	0.284124	0.080970342	0.080678
400	1.484937	1.45E+00	1.803333333	1.7824	0.32520325	0.325255	0.105757181	0.105758
450	1.844795	1.83E+00	2.01	2.003	0.36247239	0.365511	0.131386263	0.133528
500	2.320213	2.26E+00	2.254166667	2.23	0.40650407	0.406934	0.165245596	0.164723
600	3.341107	3.26E+00	2.705	2.67E+00	0.48780488	0.487226	0.237953658	0.237464
700	4.547618	4.43E+00	3.155833333	3.12E+00	0.56910569	0.569343	0.323881367	0.323105
800	5.939746	5.79E+00	3.606666667	3.56E+00	0.6504065	0.649635	0.423028725	0.422012
900	7.517491	7.32E+00	4.0575	4.01E+00	0.73170732	0.731752	0.53539573	0.533528
1000	9.280854	9.03E+00	4.508333333	4.45E+00	0.81300813	0.812044	0.660982382	0.658163
1100	11.22983	1.09E+01	4.959166667	4.89E+00	0.89430894	0.892336	0.799788682	0.797376
1200	13.36443	1.31E+01	5.41	5.35E+00	0.97560976	0.976277	0.95181463	0.951895
1230	14.041	13.72	5.54525	5.48	1	1	1	1



(a)



(b)



(c) (d)

Figure 46. Comparison between results from experiment and ABAQUS test, (a) force Vs stress intensity factor, (b) force Vs strain energy release rate, (c) stress intensity factor Vs strain energy release rate, and (d) K/K_{IC} and G/G_{IC} ratio

The error from the experiment can be calculated in comparison with the Finite Element Analysis and it measures up to 1.08% for stress intensity factor and 2.286% for strain release rate. This signifies the validity of the experiment. Furthermore, both results justify that the 30/70 composition of chopped sisal fiber and epoxy resin matrix has robust fracture characteristics with K_{IC} of 5.48 MPa.m$^{1/2}$ and critical strain energy release rate (G_{IC}) OF 13.72 MPa.mm.

Chapter 6: Conclusion and Future Work

6.1 Conclusion

Considering the increasing attention given to Natural fiber reinforced polymer matrix composites based on the possessed high strength to weight ratio, environmental friendliness and more, this study has been launched. Previous works in this area have clearly shown that synthetic and natural fibers; the likes of glass, carbon, jute, hemp and banana have been used in fiber reinforced polymer matrix composite. In this paper work, sisal fiber has been used as reinforcement and an investigation has been carried out to make use of sisal fiber made epoxy resin matrix composite. The sisal fiber was extracted manually from Ethiopian Highland sisal plant, and then the alkaline treatment was carried out. Following that, sisal fiber reinforced epoxy composite was manufactured and fracture toughness performance for each weight ratio of 15/85%,25/75%, 30/70%, 35/65%, and 40/60% was determined using experiment and the selected best mass composition, 30/70% was validated using FEM by the help of ABAQUS software. All the numerous experimental test results gathered an important information about chopped sisal fiber reinforced epoxy composite. Moreover such tests constitute fundamental confirmation of the reliability of the material and of its usage for different applications including the much acclaimed production of automotive bodies'. Based on the experimental data collected in this thesis work, few points can be concluded about the composite material.

A polymer matrix composite containing the chopped sisal fiber as reinforcement was successfully fabricated and from the fracture toughness test results it is found that 30/70 wt% have a better fracture property among the other fiber-matrix compositions. This result was also compared and validated using FEM analysis and the error from the experiment is measured up to 1.08% for stress intensity factor and 2.286% for strain release rate which signified the validity of the experiment. Furthermore, both results justify that the 30/70 composition of chopped sisal fiber and epoxy resin matrix have robust fracture characteristics with K_{IC} of 5.48 MPa.m1/2 and critical strain energy release rate (G_{IC}) OF 13.72 MPa.mm. From all the results and comparisons we can conclude that the fabricated chopped fiber reinforced epoxy composite have a good fracture toughness property and it is recommended to use it for light weight applications including production of internal door panel and Automobile dash board.

6.2 Future Work

This thesis work manly addressed the effect of chopped sisal fiber on the fracture toughness property of composite material (SFREC). But there are different related research areas which are highly important to improve the fracture property of SEREC material. Here the following topics are suggested for further studies, such as:

- ✓ Characterization of the fibers as a form of mat type and fine powder type.
- ✓ Investigate the contribution of fiber direction, orientation and volume ratio for the benefit of higher fracture toughness.
- ✓ Characterization of fibers can also be done using different fabrication techniques on SFREC's.
- ✓ Further we can make use of Advanced or Bio-Matrix materials (high density polyurethane or PEEK etc.).
- ✓ Design of natural fiber extraction processing machine
- ✓ Finding of different sisal fiber extraction and treatment processes for the better sisal fiber surface texture.

  Testing like fatigue test, shear test, impact test, moisture content test and thermal test.

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