ADDIS ABABA UNIVERSITY
ADDIS ABABA INSTITUTE OF TECHNOLOGY
SCHOOL OF MECHANICAL AND INDUSTRIAL ENGINERING
(MECHANICAL DESIGN STREAM)

EXPERIMENTAL EVALUATION OF FRACTURE TOUGHNESS AND WATER ABSORPTION BEHAVIOR OF WOVEN SISAL AND E-GLASS FIBERS REINFORCED HYBRID COMPOSITE MATERIAL

A MASTERS THESIS SUBMITTED TO SCHOOL OF MECHANICAL AND INDUSTRIAL ENGINEERING OF ADDIS ABABA UNIVERSITY IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF DEGREE OF MASTERS OF SCIENCE (M.Sc.) IN MECHANICAL DESIGN

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Declaration

I declare that the thesis presented here, entitled "Experimental evaluation of fracture toughness and water absorption behavior of woven sisal and E-glass fibers reinforced hybrid composite material" contains my own original work except I acknowledged and refereed. In addition, it meets the accepted standards concerning of the originality and quality and it has not been submitted partially or in full for a degree in any institution.

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This thesis has been submitted for examination with my approval as a university advisor.

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Thesis approval sheet

The undersigned have examined the thesis entitled "experimental evaluation of fracture toughness and water absorption behavior of woven sisal and e-glass fibers reinforced hybrid composite material" set by Oda Kerre, a candidate for the degree of master of science has successfully presented the necessary written final thesis and oral presentation and certified for partial fulfillment of the thesis requirements for the Degree of Master of Science in Mechanical Design.

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Abstract

The fracture toughness and influence of rain water aging on mode I fracture resistance of woven sisal and E-glass fibers hybrid composite material is experimentally studied in this paper. The sisal fibers were extracted from the sisal plant manually. 5% NaOH was used for the sisal fiber surface treatment. Then the woven sisal fiber (mat form) was prepared from treated fibers by hand weaving. Test specimens of woven sisal and randomly oriented E-glass fiber with polyester resin as a matrix material are used in this study. The manufacturing techniques was hand layup process. Compact tension specimens for mode I and rectangular specimens for rain water absorption conditions are used to realize the test. These specimens were categorized to be immersed in rain water for one week period of time to visualize the effects. The results of the experimental work showed that, the mode I fracture toughness value of K_{IC} =10.2 MPa. √m and K_{IC} =16.68 MPa. √m respectively for 2mm and 5mm specimen thickness, which is resulted in the normal specimen test. The water absorption tests were carried out through immersion in rain water for 7 days and the maximum water absorption of the hybrid specimen was 0.063% and 0.034% respectively for 2mm and 5mm thickness. Also, due to rain water aging of the hybrid specimen of 5mm thickness for 7 days in rain water, the fracture toughness value of the hybrid specimen was decreased by 3.94 MPa. √m. The fracture toughness of rain water exposed specimens are lower compared to the normal specimens in a compact tension test.

Keywords: Fracture toughness, Glass fibers, Hand layup, Hybrid composite materials, Water absorption, Polyester resin, Sisal fibers, Stress intensity factor (K_{IC}).

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List of Abbreviations and Acronyms

ASTM	America Society for Testing and Material
CT	Compact tension
UTM	Universal testing machine
W_f	weight of Fiber (g)
W_m	weight of Matrix (g)
W_c	weight of composite specimen (g)
ρ_f	Density of Fiber (g/cm^3)
ρ_b	Density of bamboo fiber (g/cm^3)
ρ_m	Density of Matrix (g/cm^3)
V_f	Volume of fibers, (cm^3)
V_m	Volume of matrix, (cm^3)
V_C	Volume of Composite specimen (cm^3)
W_F	Fiber weight fraction
W_M	Matrix weight fraction
V_F	Fibers Volume fraction
V_M	Matrix Volume fraction
h	Ply thickness (mm)

Chapter 1: Introduction

1. 1. Introduction

Nowadays, the application of hybrid composite materials has been recently increased in the field of aerospace, automobile, nuclear, marine, biomedical and in other engineering areas due to following reasons; high strength or stiffness for lower weight, superior fatigue characteristics, and facility to change fiber orientations etc. [1].

Natural fibers and synthetic fibers are used for the reinforcement in the hybrid composites [2]. Even though, synthetic and natural fibers have their own advantages and have great role for the reinforcements in hybrid composites, both synthetic and natural fibers have also their own drawbacks like recycling, reusability, and biodegradability problems for synthetic fibers and as well as high moisture absorption and poor mechanical properties for natural fibers [3]. The hybridization of natural fibers with synthetic improves the performance and minimize the drawbacks that comes from both natural fibers and synthetic fibers by taking the advantage of both natural and synthetic fibers [4, 5].

At the same time, hybrid composite materials are exposed to different problems such as inter ply-cracking, voids, discontinuities and fiber cracking. Among these three problems, mode I fracture toughness is a common failure mode in the hybrid composite materials. The fracture mechanism is very complicated and many factors will influence the failure process [6].

The service conditions of products that made from these hybrid composite materials are exposed to different environmental conditions. Hence, it is found that the effects of the media or environmental condition should be studied. As already known that the uses and advantages of hybrid composite materials over metals were found preeminent and the best alternative [7].

As mentioned, due to many advantages, recently most researchers give an attention on the fracture toughness of hybrid composite materials. In this paper, there are rain water conditioning taken into consideration by undertake the service situations of products of these materials may exposed into rainy environments and compact tension specimens were prepared for fracture toughness test. The estimation of crack length after the initial crack has been generated by software integrated with universal testing machines during test. The test has been developed on the universal testing machines unto the guidelines from ASTM standards and results were obtained accordingly.

1.2. Statement of problem

Nowadays, natural fibers hybrid composite materials are used for engineering applications due to the advantages of renewability, cost-effective, lightweight, and eco-friendly when compared with the synthetic composite materials that have their own disadvantages such as easily melting and burning, non-biodegradable, cause soil pollution and etc. [3, 8].

However, having those natural and synthetic fibers independently we may have some difficulties and as well the application of natural fibers is limited to some extent due to their disadvantages such as water absorption, thermal instability, strength degradation, and poor impact properties [9].

Therefore, the hybridization of synthetic fibers with natural fibers minimizes the drawbacks that comes from both fibers and improves the tribological, mechanical, and physical properties than having those fibers independently [10]. Therefore, studying hybrid composite materials further by integrating different components of the composite's ingredients to take advantage of both natural and synthetic fibers is very essential.

Also, hence the fracture toughness play great role in the application of fracture mechanics are for damage tolerance design, structural integrity assessment and residual strength analysis for different engineering components and water absorption test under specified conditions especially in climates subjected to heavy rainfall and freezing and thawing cycles for interior or exterior applications.

So, the problem being addressed in this study is to investigate experimentally fracture toughness behavior and effect of rain water absorption on fracture toughness of hybridized woven sisal and E-glass fibers reinforced polyester hybrid composite for engineering applications under mode I loading condition.

1.3. Objectives

The objective of this study is an experimental evaluation of fracture toughness behavior and effect of rain water absorption on fracture toughness of woven sisal and E-glass fibers reinforced polyester hybrid composite material under mode I loading condition.

The specific objective of this theses includes:

- Evaluate fracture toughness value of developed hybrid composite.
- Study and determine the water absorption value of the developed hybrid composite.
- Investigating the effect of rain water media on fracture toughness value of developed hybrid composite.

1.4. Scope of the study

The research presented here focuses on the determination of the fracture toughness value and investigating the effect of rain water media on the fracture toughness value of woven sisal and E-glass fibers reinforced polyester hybrid composite material under mode I loading condition based on ASTM standards and the results are obtained accordingly. The evaluation of fracture toughness of compact tension specimens under mode I loading condition were studied only by experimental work, comparisons by an analytical and by numerical methods are left for future works.

1.5. Limitations

In order to have values that are more accurate in fracture researches, proper laboratory setup and testing machines should be available. Shortages are an unavailability of highly competitive testing laboratory setup; an appropriate band saw blade thickness for specimen's crack initiations and an appropriate universal testing machines for hybrid composite materials that fits for different sized and designed specimens as per ASTM.

1.6. Methodology

Methodology is a systematic approach and theoretical analysis of various methods applied to a field of study. For this thesis work, figure 1 shows the methodology flow chart that used to perform objectives of the thesis.

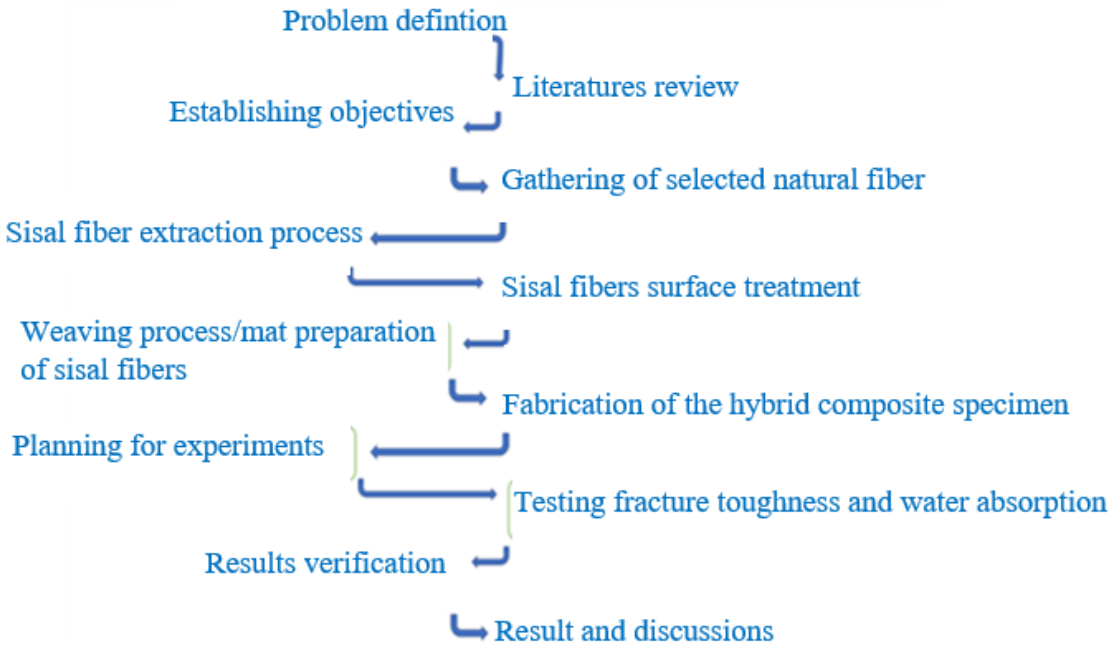


Figure 1: Methodology flow chart

1.7. Paper organization

This work is organized into five chapters. The first chapter introduces the background of natural fiber, synthetic fiber composite materials, and hybrid composite materials, the problem of the statement; general and specific objectives. The second chapter presents a literature review on hybrid composite materials, natural fibers composites, synthetic fibers composites, composite's chemical and mechanical properties, different theory's which are used for the predication of fracture toughness and water absorption parameters. The third chapter deals with the experimental set up and procedures which focused on materials, test piece preparations, experimental methods, conditions, and test set up for mechanical and physical tests of sisal-glass fibers hybrid composite. The fourth chapter states the laboratory fracture toughness and water absorption test results and discussions and the last chapter reports the conclusions and recommendations.

Chapter 2: Literature review

2. 1. Composite materials

Composite materials are materials that are made from two or more ingredients with unlike chemical, physical, mechanical, or other assets/properties, that remain different within the ended structure. Composite materials ingredients involve a matrix strengthened with filaments or particles. Natural fibers were used for reinforcing the matrix at the beginning of the mid-20th century. However, the demand for natural fibers increased since 1950 in the environments of construction, transportation, and aerospace. Because when compared with engineering materials such as metals, natural fibers reinforced composite materials have better advantages such as higher strength, low specific gravity, lightweight [11, 12]. Classification of composite materials depends on the reinforcement methods as shown in figure 2 below and the kind of matrix (i.e., such as ceramic, metal, polymer composite) [1, 13].

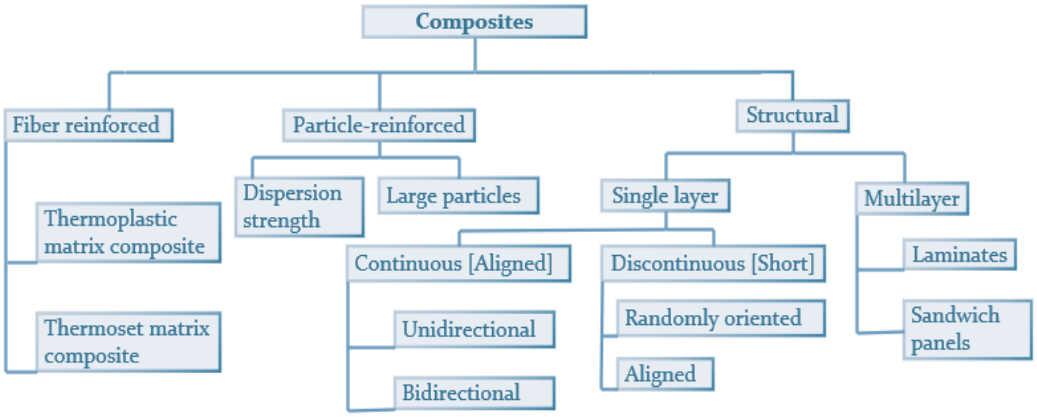


Figure 2: Composite materials classification *[12]*

Composite materials of fiber-reinforced, classified as short and continuous fiber-reinforced composite materials. Short fibers can be in the form of chopped and random to the required size and length for reinforcement. Composite materials performance is determined by reinforcement and matrix adhesion. Composite materials made of continuous fiber-reinforced often contain a laminated structure. As drawback in continuous fiber-reinforced, continuous fibers render matrices applications and slurring of fibers during molding [14].

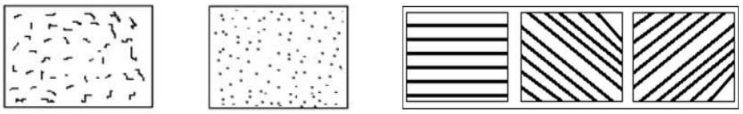


Figure 3: a) Short fiber and b) Continuous fiber reinforced composites sub-classification *[14]*.

2.1.1. Laminated composite materials

Characteristics of composite materials depend on the fraction of matrices and reinforcements, reinforcement, and manufacturing methods. Individual plies that bonded together to their principal plane forms a laminate [15, 16] Composite laminates are shaped by stacking various plies through different angles and alignments [17, 18]. Consideration of stacking arrangement of plies and to be mindful of symmetry and balance of the stack is important when designing laminate. symmetric stack helps to remove any bending or warping tendency [18].

The composite material of fiber-reinforced, manufactured by a combination of fibers into a thin layer of the matrix to produce a lamina (ply). Lamina construction from continuous fibers and discontinuous fibers arranged either in unidirectional, bidirectional, and in multi-directional orientation [19]. Several laminas are stacked and joined together in the specified orientation to form laminate in order to get the required thickness that maintain a given deflection or support a given load in a composite of fiber-reinforced [14]. The range of lamina thickness is usually 0.1mm – 1mm [20].

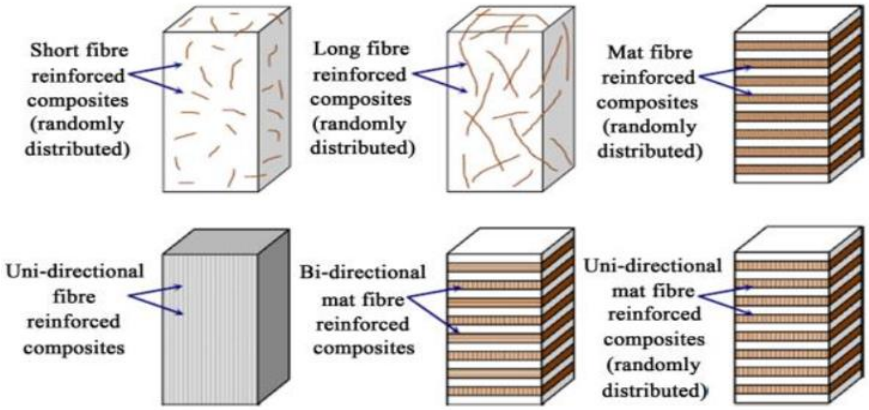


Figure 4: Different types of fibers orientation used for laminate manufacturing *[19, 14]*.

Based on fibers, composite materials classified as natural fiber composites and artificial (synthetic) fibers composites materials [19]. Natural fiber composites are made from natural resources such as sisal, bamboo, kenaf, hemp, banana, etc. [21] and synthetic fiber composites materials are man-made composites materials shaped from artificial fibers such as carbon, glass, etc. [8].

2.2. Synthetic fibers

Synthetic fibers are artificial fibers that used for the reinforcement such as carbon, glass boon, and aramid. Among the synthetic fibers, glass fibers are commonly used as reinforcement due to its

abundance and low cost. Common reinforcement forms of glass fibers are continuous fibers (that used for fiber weaving, winding, and braiding), discontinuous fibers (that made by cutting continuous fibers), woven fabrics used for laminates design that used for a variety of applications such boating, sporting, and marine and multidirectional fabrics [22, 3].

Synthetic glass fiber composites lack in various aspects like recycling, reusability, and biodegradability problems at the end of their useful life. The synthetic fibers have better resistance to moisture absorption, whereas the natural fibers aren't. Hence a natural fiber can be combined with a synthetic fiber to take the best advantage of the properties of both the fibers as well the advantages of one type of fiber could compensate for the lapse in the other one.

2.2.1. Glass fiber

Synthetic fibers are classified into organic and inorganic fibers. Glass fibers are known as fiberglass among inorganic fibers that are used as reinforcements in composites materials [23]. Glass fiber has high strength, low cost, better for chemical resistance and low density. Glass fibers classified as C-glass is used as strengthening for corrosive barriers in a chemical plant to improve surface finish, D-glass is used for application needs low strength, E-glass is used for beautification, structural, electrical applications, and S-glass has a high content of silica and high fatigue strength, and used for aerospace applications [24]. Unlike Kevlar or carbon fiber, glass fibers are isotropic thus avoiding loss of properties when loaded in the transverse direction [25].

2.3. Natural fibers

The natural fibers are category of renewable sources of reinforcements and complements for composite materials. Natural fibers composites are mostly used in military applications, building and construction industries (ceiling paneling, partition boards), transportation (automobiles, railway coaches, aerospace), packaging, etc. as alternative for the synthetic fibers due to their advantages of eco-friendliness, lightweight, non-toxic and harmless, recyclable, biodegradable, high toughness, renewability, and low emission of pollutants. As a result, the demands for natural fibers have increased drastically due to its desired characteristics when compared to synthetic fibers, etc. [8].

Water molecules enter and get attached to the hydrophilic groups of fiber, forming intermolecular hydrogen bonding with fiber and reduce fiber-matrix compatibility when natural fiber composites are exposed to a humid environment [26, 9]. The mechanical and moisture absorption properties

of natural fibers composites are significantly influenced by the interfacial bonding between the fiber and the matrix. To enhance the interfacial bonding between them, adhesion has to be improved by fiber surface treatments using alkaline solutions [27].

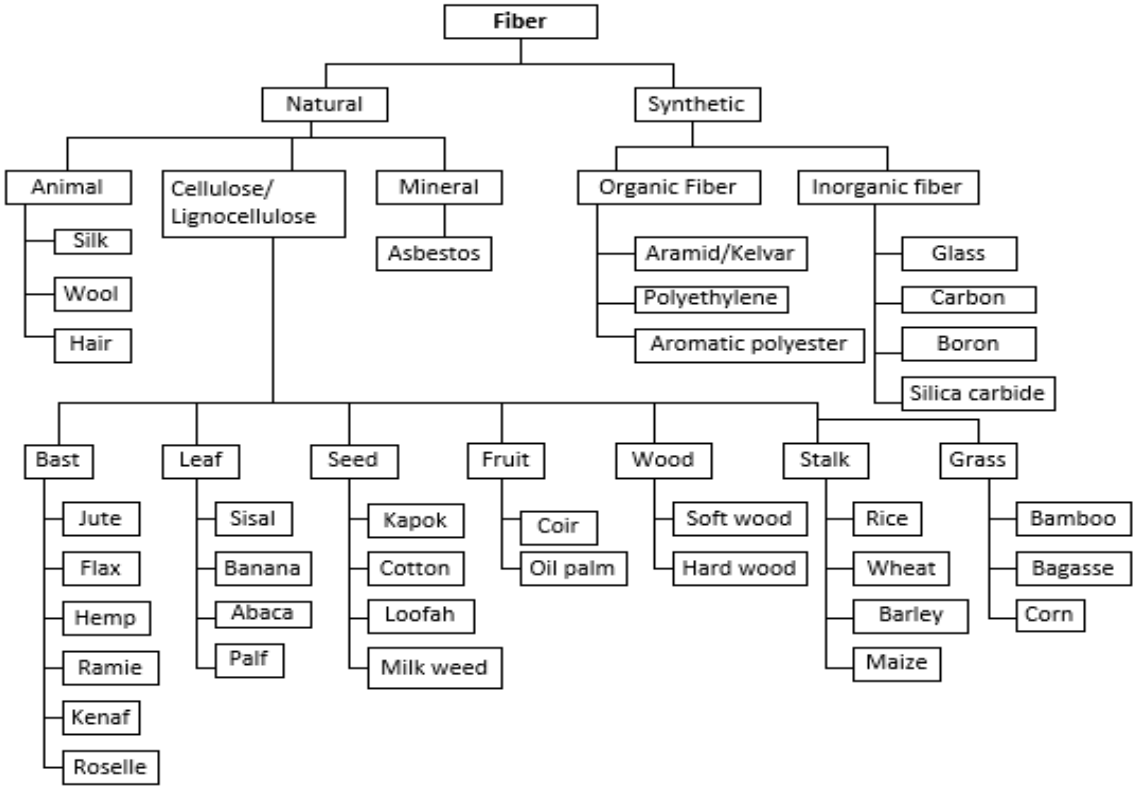


Figure 5: Classification of fibers *[28]*

2.3.1. Sisal plant

Sisal plant is grouped under hard fibers that strong, yield stiff, and durable fibers used for various applications [29, 30]. The cultivation process of the sisal plant is simple and it can grow in all kinds of the environment [31]. The life span of the sisal plant is 7-10 years and closely produces about 200-250 leaves [32]. Sisal leaf weighs about 600 g and each leaf yields about 1000 fibers [33]. The average length and width of the sisal leaf are 1.5 m and 15 cm respectively and the diameter of the fiber is on average between 100 and 300 µm [34].

Figure 6: A representative view of sisal plants and sisal fibers

2.3.2. Sisal plant in Ethiopia

Ethiopia has a fertile ground and delightful potentials in Amara, Oromia, Tigray and SNNPRS regional state to harvest sisal plant on the small and large-scale foundation. Nevertheless, the production and cultivation process of the agave sisal plant is relatively minimal. It is cultivated, harvested, and collected only by farmers to use it for their primary purposes such as ropes [35, 36].

2.3.3. Sisal fiber

Sisal fibers are extracted from the sisal plant by mechanical methods [31, 37]. Mechanical extraction methods give good quality of fibers having lustrous color whereas retting extraction methods yield fibers with poor quality. Fibers are washed by normal water to remove excess waste like chlorophyll, leaf juice, and adhesive solids [38, 29]. Sisal fiber has advantages like high specific properties, low cost and density, eco-friendly and bio-degradable, relatively strong and stiff, good dimensional stability, harmlessness, recyclability, short growth cycle, and high availability. Traditionally, it is being used as natural ropes, carpets, clothing, and other reinforcement materials [39].

Several groups of researchers reported chemical compositions of sisal fiber as shown in table 3. The presence of lignin content in sisal fiber is higher than the other natural fiber plants such as jute, pineapple fiber, etc. [40].

2.3.4. Textile structure of sisal fibers

Textile structures play a great role in the reinforcement of composite materials due to mechanical performance such as high strength, modulus, and toughness, conformability, and processability. Manufacturing of textiles based on weaving, braiding, and knitting processes [41, 42]. Woven fabrics textile structures are better than others that are used as reinforcement in composites due to their good mechanical characteristics, conformability, design possibility with different orientations and allow easy production processes [43]. When compared with unidirectional fiber allow reinforcements, woven fabrics have balanced properties [44].

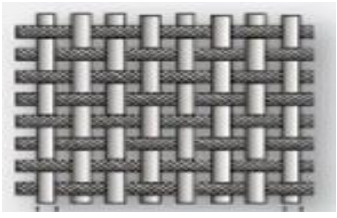


Figure 7: Woven fabrics textile structures

2.3.5. Direct and indirect applications sisal fiber-based composites

Sisal fiber can be used directly as twines (used for weaving carpets), ropes (prepared by twisting the twines), yarn (used to make rope or cables), fabrics, buffs (produced from yarns for polishing the shoes and handbag design purpose), mattresses, and floor coverings, etc. As indirect applications, sisal fibers are used in composites materials as noise absorber, insulator, and impact load absorber. Composite of sisal fibers are used in agricultural industries, construction materials, automobiles, aerospace, rail engines, and electrical applications [30]. Inorganic fibers (glass, asbestos, etc.) have several disadvantages such as non-bio degradability, abrasion when it rubs with other parts, and human health problems during processing, and handling of these fibers. Where as sisal fibers are biodegradable, it is eco-friendly and less abrasive [37].

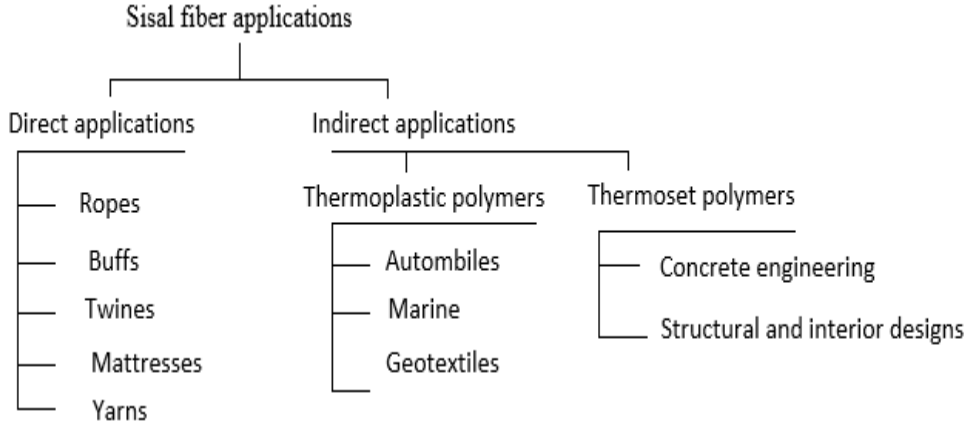


Figure 8: Various applications of sisal fiber *[37, 30]*.

2.4. Matrix materials

Parallel to reinforce, the matrix is also an important element and a continuous phase in the composite. They hold everything together and transfers mechanical loads through the fibers to the rest of the structures and are used to bind the fibers together with a matrix. It also protects materials from environmental factors such as abrasion, impact, humidity, and corrosion [45, 46]. Composite materials are fabricated by reinforcing the fibers with thermoset hydrophobic matrixes such as polyester, phenolic, melamine, silicones, polyurethanes, and epoxies. Matrix materials are classified as in figure 9 below [47, 48].

2.4.1. Thermoset matrices

Thermoset matrices are characterized by their dimensional stability, rigidity, electrical, and thermal insulation properties. Forms of thermoset matrices are viscous liquid and powder resin [49].

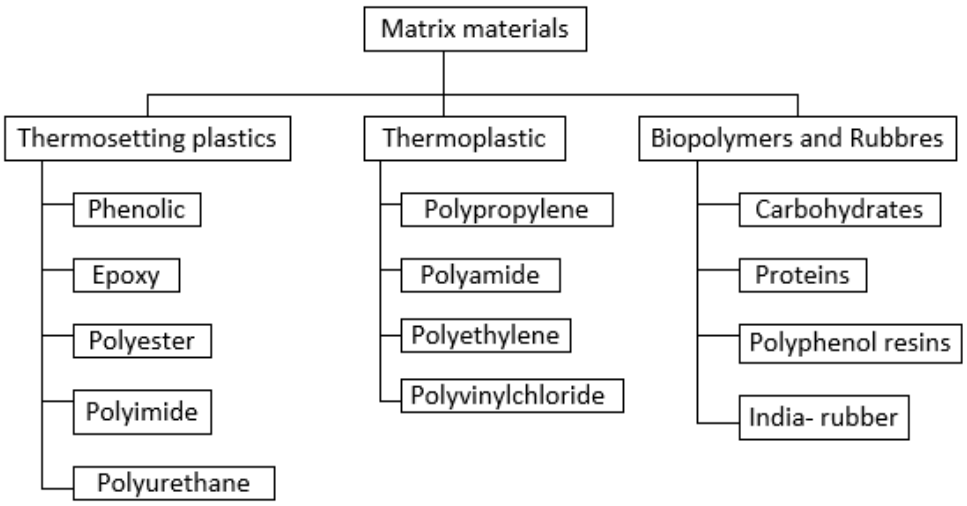


Figure 9: Classification of matrices *[47, 48]*.

2.4.2. Polyester resin

Polyester resins are used in various applications including construction materials, aircraft bodies, automotive, marine, packaging, furnishing, and textile industries [50]. It can form the desired shape. It can be wet or dry and it dries very quickly. It has resistance to stretching and wrinkling. Moreover, polyester offers resistance to shrinking, abrasion, colorless, and transparent. When it burned, it gives off a strong odor. It is harmful in molten form when it comes in contact with human skin [49].

2.5. Hybridization of natural fibers and synthetic fibers

Hybridizing natural fiber by synthetic fibers is one of effective method that used to achieve better mechanical properties such as improving strength and stiffness, thermal stabilization, fatigue and moisture resistance than mechanical properties of natural fibers [10]. Commonly, hybridization of natural with synthetic fibers offers a technique to improve properties of materials over natural fibers alone [51, 52].

2.6. Concept of fracture mechanics and fracture toughness

Fracture toughness is the property, which is an indication of the amount of stress required to propagate a pre-existing flaw. It is a very important material property since the occurrence of flaws are not completely avoidable in the processing, fabrication, or service of a material/component. Flaws may appear as cracks, voids, metallurgical inclusions, weld defects, design discontinuities, or some combination thereof. Since engineers can never be totally sure that a material is flaw free, it is common practice to assume that a flaw of some chosen size will be present in some number of components and use the linear elastic fracture mechanics (LEFM) approach to design critical components. This approach uses the flaw size and features, component geometry, loading conditions and the material property called fracture toughness to evaluate the ability of a component containing a flaw to resist fracture [53].

Suppose the load on the specimen is increased until it breaks, i.e., fracture as shown in the figure 10. The resistance to this fracture may be characterized by the stress intensity at fracture, K, called the fracture toughness. A stress intensity, K value represents a lower limiting value of the material's fracture toughness. This value is used to estimate the relation between failure stress and defect size for a material in service where conditions of high tensile loading would be expected [54].

2.6.1. Stress distribution around a crack

Consider the cracked material specimen in figure 10. In the immediately vicinity of the crack the material does not behave in a linear elastic fashion and thus the large stresses predicted by LEFM and the above equation are not realized. In a metal, plastic yielding occurs to relieve and redistribute the stress. In other materials, such as polymers or ceramics, different types of deformation, such as crazing or micro-cracking, may occur. For plastics, the material is usually so brittle that stress concentration within the specimen will result in rippling. The above equation is also unrealistic far from the crack where the shape of the specimen and the loading conditions determine the stress field. In between these regions, however, is a region where the crack dominates the stress field and the material deforms elastically. This is called the region of K dominance. Equation (3.1) is valid in this region [55, 56].

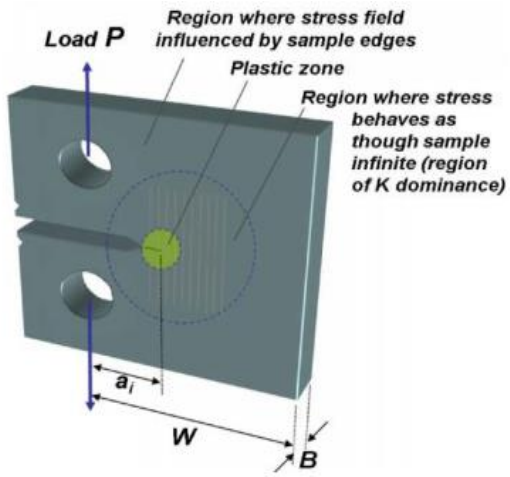


Figure 10: Finite cracked sample subjected to point load *[56]*

2.6.2. Modes of Fracture

Figure 11 defines the three modes of loading: Mode I (opening or tensile mode), Mode II (sliding or shear mode), and Mode III (tearing mode). Fracture mechanics concepts are essentially the same for each mode. However, the great majority of all actual cracking and fractures cases in metals are mode I problems. A crack in the very early stage of development will turn into a direction in which it experiences only Mode I loading, unless it is prevented from doing so by geometrical confinement. For this reason, fracture mechanics of metal is generally confined to Mode I [57, 54]. A roman numeral subscript indicates the mode of fracture and the three modes of fracture are illustrated using figure 11.

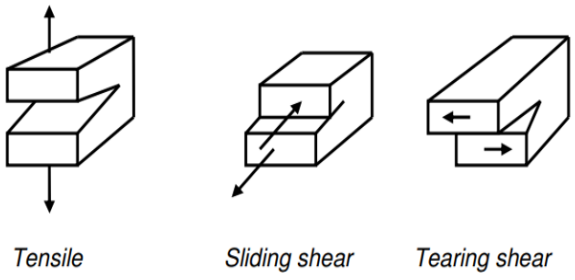


Figure 11: Loading modes

A cracked body can be loaded in any one of these modes, or a combination of two or three modes. Mode I fracture is the condition in which the crack plane is normal to the direction of tensile loading. This is the most commonly encountered mode.

2.6.3. Stress Intensity Factors (S_{IF})

The stress intensity factors are used as a measure that quantifies the severity of a crack relatively to others cracks. According to the linear elastic fracture mechanics, the behavior of a crack in any brittle material can be characterized completely by a single parameter known as the stress intensity factor (S_{IF}) [58].

For compact tension specimen (ASTM D 5045-99):

The fracture loads P, obtained from the tests are used to determine S_{IF} values (MPa. √m) as a measure of fracture toughness by using the following data reduction scheme.

$$S_{IF} = \left\{\frac{p}{B\sqrt{w}}\right\} f(x) \quad \text{.....2.1}$$

Where: B = specimen thickness, cm, w = specimen width, cm, a = crack length, cm and

$$f(x) = \frac{(2+x)(0.86+4.64x-13.32x^2+14.72x^3-5.64x^4)}{\sqrt{(1-x)}}, \qquad \text{Where: } x = \frac{a}{w},\ 0.45 < \frac{a}{w} < 0.55$$

2.6.4. Data reduction

Researchers have used test standards from ASTM D E399 of the isotropic materials to calculate stress intensity factor to characterize toughness of laminated composite materials using CT specimen. Usually, the fracture behavior of materials expressed in terms of critical strain energy release rate which represents the energy required for crack growth. The G_{IC} of orthotropic laminated plate with the pre-crack under mode I loading can then be calculated from K_{IC}.

$$G_{IC} = \frac{(KIC^2)}{E*} \quad \text{.....2.2}$$

Where E is the equivalent module of composite given by:

$$E* = \frac{\sqrt{2E1E2}}{\sqrt{\sqrt{\frac{E1}{E2}} - V12 + \frac{E1}{2G12}}} \quad \text{.....2.3}$$

There are four data reduction schemes.

Area method

For the energy area method, the change of strain energy in the material can be calculated using the area under the load vs load line displacement curve from the loading point 1 to 2 as shown in fig 3.4. The crack length that changes by a value Δa represents the dissipated energy during the crack propagation and is indicated by shaded region. This method is among the simplest method of data reduction. The critical strain energy released can be calculated by:

$G_{IC} = \frac{1}{2*t*\Delta a}(p_1d_2 - p_2d_1)$ …….2.4

Where: P_1, P_2 are loads and d_1, d_2 are displacements at the points 1 and 2, respectively.

Compliance calibration method

A number of means are available by which the material property G_{IC} can be measured. One of these is known as compliance calibration method, which employs the concept of compliance as the ratio of deformation to applied load.

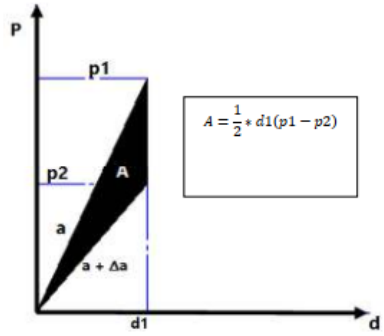


Figure 12: Load vs displacement curve of area method

Where p1 is load 1 at displacement 1 and p2 is load 2 at displacement 2, δ is crack opening displacement.

$C = \frac{\delta}{p}$ …….2.5

The total strain energy U can be written in terms of this compliance as:

$U = \frac{1}{2}p\delta = \frac{1}{2}cp^2$ ……..…….....2.6

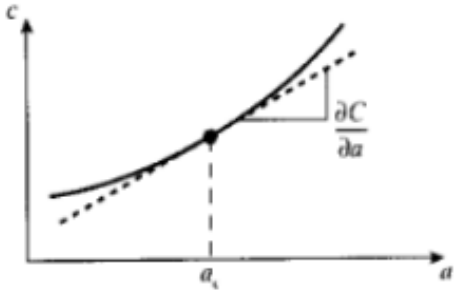


Figure 13: compliance as a function of crack length

The strain energy release rate can then be determined by differentiating the curve of compliance versus length:

$G_I = \frac{dU}{da}$ ……...……...2.7

J-Integral method

For a linear orthotropic material under mode-I loading the G_{IC} can be equated with the J-Integral proposed by Rice.

But, for this thesis work we are going to use the compliance calibration method.

2.7. Water absorption effects on hybrid composite materials

Water absorption in natural fibers reinforced composites can affect the mechanical properties of a part by degrading the fiber matrix interface, microcracking the matrix, changing the stress state, and altering the glass transition temperature [7]. Over time composite materials absorb water from the surrounding environment. In order to ensure reliability of the mechanism and to determine the time that the mechanism can be in a real-life environment before water absorption damages structural integrity, a variety of tests are performed on samples that have undergone accelerated exposure to simulate 'end of life' water content usually defined as service moisture content.

The desired water content is reached once the part equals the weight that is calculated using the 1D Fick's' equation. A computational model can be created using Fick's 2nd law of diffusion in 1D to determine the target moisture after ten years. Fick's model could indicate whether a shorter time period in the chamber would obtain the same accurate results as the present mandatory time [59].

Fick's 1st Law. Fick's 1st law explains the diffusion or flux of molecules from areas of higher concentration to areas of lower concentration, where flux is proportional to the rate of change of concentration with respect to position [59].

$$J = -D\frac{\partial \emptyset}{\partial z}$$

Where, J is the diffusion flux, D is the diffusion coefficient or diffusivity and ∅ is the concentration in dimension of moles per unit length.

Fick's 2nd Law. Fick's second law, derived from Fick's first law, allows for the calculation of the water content at a given location in the material at any given time. The concentration of the substance in a Δx length of material during a Δt time interval is approximately. For the case of one-dimensional moisture diffusion [60].

$$\frac{\partial c}{\partial t} = D_z \frac{\partial^2 c}{\partial z^2}$$

Where, c is the moisture concentration, D_z is the moisture diffusion coefficient, z is the distance through the thickness and t is the time.

When composite materials immersed in water over time and absorb water from the surrounding environment, the absorbed water degrade the fiber matrix interface, microcrack the matrix. Therefore, since water absorption properties has negative effect on the mechanical properties of materials, load conditions also effected by absorbed water. For over time immersed specimens, absorptions of water will be more. Due to this over immersed specimen needs lower loading conditions since degradation of fibers matrix interface and microcracking of the matrix affected by absorbed water that lower the adhesion properties of the specimens.

2.8. Overview of related previous works

The fracture toughness of different composite materials based on several parameters was studied on different literatures. Studies try to investigate enhancement mechanisms of fracture toughness by introducing different interleaves and the effects of different environmental conditions on fracture toughness behavior of composite materials. Among the several literatures that are related to the fracture toughness and water absorption of composite materials, some are listed below.

P. K Dash et.al. (2004) investigated the effects of the environment on fracture toughness of woven carbon epoxy composite after exposing to various adverse environments, like, water, saline water, acidic water, organic fuel, ice temperature, and hot air of 60°C, for different durations using single edge notched specimens. The fracture toughness has been found to decrease continuously with increased duration of environmental exposure. After exposure to various environments, it has been found that debonding occurred in the initial phase of fracture toughness testing. It has been observed that the temperature has a significant influence over matrix debonding and reduced the original strength in a greater margin. In the case of a liquid environment, the density of the medium has a significant influence over the rate of diffusion of moisture into the material. It depends on the constituent particles of the liquid; its osmotic pressure and the number of voids in the material [61].

George C. et.al. (2005) made a review of the works done in the past to investigate the strain rate effects on the Mode I, Mode II, and Mixed Mode fracture toughness properties of fiber-reinforced

polymer composite materials. From the review, the result shows and summarize that the transition from a ductile to a brittle failure mode with increasing loading rates is accompanied by a reduction in the fracture toughness of the composite with increasing loading rates. [62]

A.K.M. Masud.et.al. (2007) investigated the effects of the environment on fracture toughness of glass fiber-polyester composite after exposing to various adverse environments, like, water, saline water, acidic water, organic fuel, ice temperature, and hot air, for different durations using a single edge notched specimen. The result shows that the fracture toughness has been found to decrease gradually with increased duration of environmental exposure. The highest amount of degradation in fracture toughness was found after exposure into acidic water and then in low temperature followed by high temperature, organic fuel, water, and saline water for the same duration of exposures [63].

P.S. Shivakumar Gouda et. al. (2011) investigated Mode-I fracture behavior of glass-carbon fiber reinforced hybrid composite experimentally and by finite element analysis using compact tension (CT) specimen. The result indicated that the cracked specimens are tougher along the fiber orientations as compared with across the fiber orientations, the elastic modulus of the tensile specimen and the magnitude of the critical stress intensity factor (K_{IC}) of the CT specimen are dominant in along the fiber orientation. Also, the finite element result indicates that the magnitude of the critical stress intensity factor (K_{IC}) is dominant in along the fiber orientation of the CT specimen [64].

V. Santhanam et.al. (2013) studied the effects of chopped glass fiber and banana fiber content on the mode I fracture property of polyester composites. Fracture toughness tests were performed on glass fiber and banana fiber reinforced polyester composites with fiber fraction volume percentages of 13%, 17%, 20% volume fraction. it is observed that the fracture toughness of banana fiber-reinforced composite is in close agreement with a glass fiber [65].

Prakash Chandra Gope et. al. (2015) studied the effect of banana, bagasse, coconut fibers and silica, walnut shell particles on the fracture toughness. Epoxy resin was used as matrix material and different bio-fibers such as banana fiber, bagasse fiber, coconut fiber and particles such as silica and walnut shell particles with different wt% are added as reinforcing material. The mode I fracture toughness tests are conducted and the results show that among the bagasse, banana, and coconut fibers, bagasse-based composite is found to be superior with respect to the fracture

toughness value. also, the result showed that hybridization of fibers with particles such as silica and walnut shell improves the fracture toughness values of the composite drastically [66].

Shashank T.A. et.al. (2016) investigated fracture toughness of woven banana fibers reinforced with glass fiber as a natural hybrid composite and the results signified that the fracture toughness improved in banana-glass hybrid composite with increased glass fiber content from 5%-15%. The glass fiber provides toughness and banana fiber provides elasticity to the composite. The fracture toughness of the composites depends on many factors like fiber content, fiber strength, fiber length, modulus, orientation, and fiber-matrix interfacial bond strength [67].

S¸aziye Arasan (2016) investigated the effect of crack length and crack location on the fracture toughness of woven glass-carbon reinforced hybrid and non-hybrid composite plates experimentally and numerically. The specimen of non-hybrid composite plates (glass-epoxy, carbon-epoxy) and hybrid composite plates (glass-carbon-epoxy and carbon-glass-epoxy) were produced by using hand lay-up method. The fracture toughness of hybrid and non-hybrid composite plates having three different crack locations as single edge crack (SEC), center crack (CC), and double edge crack (DEC) with different crack lengths were obtained by determining failure loads under tensile loading. The results showed that the highest and the lowest fracture toughness values were obtained in the specimens with SEC and CC, respectively. Although hybrid and non-hybrid composite specimens have the same crack length, the order of fracture toughness from the highest to the lowest occurred in the specimens with SEC, DEC, and CC, respectively [68].

Harish K. Patel et.al. (2017) investigated the fracture toughness properties, in terms of stress intensity factor K_{IC} and strain energy release rate G_{IC}, of hemp fiber mat-reinforced composites using the compact tension method and compared with those of glass fiber-reinforced composite. Three material parameters were considered for composite optimization: fiber volume fraction, CaCO3 filler content and hemp fiber surface treatments using alkaline treatments. The highest fracture toughness for hemp fiber mat-reinforced composites were obtained at a fiber loading of around 30 vol.-%, while it was also shown that the fracture toughness properties of hemp fiber mat-reinforced composites are sensitive to mineral filler content. Surface treatment of the hemp fibers using a combined alkaline-silane treatment resulted in a significant improvement in fracture toughness of hemp fiber mat-reinforced composites. Optimized hemp fiber mat-reinforced

composites exhibited fracture toughness properties similar to those of glass fiber-reinforced composite at fiber contents of 20 vol.-%, with K_{IC} values of around 6 $MPa.m^{1/2}$ [69].

Araya Abera et.al. (2018) conducted experimental analysis on sisal fiber-based bio-composite using compact tension specimen, to find the composite with good fracture toughness through varying sisal fiber and epoxy ratios. The result showed that 30/70 mass composition has better mechanical and fracture property compared with other mass compositions. The fracture toughness increases with increasing sisal fiber content up to 30 wt.% [70].

Sandhya Rani Borukati.et.al [2018] conducted a design and characterization of E-glass fiber-reinforced composite material with the use of sisal fiber. From the result, the E-glass fiber reinforced composite material with adding of sisal fiber is more advantageous for aerospace and automobile applications, due to the Hardness, tensile, compression, impact characteristics of E-Glass fiber-reinforced sisal composite the material gives better mechanical properties than ordinary E-Glass fiber composite material [71]**.**

P.V. Josef et.al. (2002) studied the environmental degradation behavior on the physical and mechanical properties of short sisal-polypropylene composites with special reference to the influence of aging conditions like treatment with water and UV radiation. The water absorption characteristics of sisal- polypropylene composite was studied by immersion in distilled water with special reference to fiber loading, fiber orientation, chemical treatment, and temperature. Water uptake of the composite was found to increase with fiber content and leveled off at longer periods. The chemically modified fiber composites showed a reduction in water uptake because of better interfacial bonding. This is because all chemical treatments are given to sisal fiber reduce its hydrophilicity thereby favoring strong interfacial adhesion between the fiber and polypropylene matrix. Water uptake of the composite was found to increase with temperature since temperature activates the diffusion process [72].

E. M. F. Aquino et. al. (2007) studied the moisture absorption effect on the mechanical properties of a hybrid sandwich composite formed by polyester resin, reinforced by bi-directional woven fabrics of glass and jute fibers, with a central layer of polyester fabric (core mat). For the composite characterization, were performed tensile and three-point-bend tests, damage mechanism analysis,

and moisture absorption tests. A larger absorption was observed for the hybrid composite compared to commonly observed fiberglass composites. The absorption rate is significantly higher in the first 30 days (comprising 63% of the total absorption), compared to the total time. For fiberglass composites, the saturation is reached usually in 2 or 3 months with a weight increase of approximately 1.5%. It is well known that vegetal fibers absorb high moisture due to its hydrophilic nature. Among the components of the vegetal fiber, hemicellulose is mainly responsible for fiber moisture absorption, although lignin and non-crystalline cellulose also have their importance [73].

Mohd Hafiz Zamri et.al (2008) studied the water absorption of pultruded jute/glass-fiber-reinforced unsaturated polyester hybrid composites, which was subjected to various water conditions and their effects on its mechanical properties. Water absorption tests were performed by immersing composite specimens into three different water conditions, namely: distilled water, seawater, and acidic water, which were at room temperature, for 3 weeks. Observed from the result, the water absorption the behavior of the glass/jute fiber-reinforced unsaturated polyester hybrid the composite was found to follow a non-Fickian behavior [74].

Z. Salleh et.al. (2012) investigated the effect of water absorption on mechanical properties of long kenaf-woven glass hybrid composite. The rates of the moisture uptake by the composite's increases with immersion time and exhibit non-Fickian behavior. Exposure of the natural fiber composite material to environmental conditions such as distilled water, sea water and rainwater results in decreasing of fracture toughness. The decrement of the fracture toughness may be due to the water absorption characteristic depends on the content of the fiber, fiber orientation, area of exposed surface, the permeability of fiber, void content, and the hydrophilicity of the individual component [75].

Manickam Ramesh et. al. (2016) studied experimentally the effect of fiber orientation and fiber content on properties of sisal-jute-glass (in the ratio of 40:0:60, 0:40:60, and 20:20:60 respectively) fiber-reinforced polyester hybrid composites. The results indicated that the hybrid composites had shown better performance and the fiber orientation and fiber content play a major role in strength and water absorption properties. The result showed that the composites absorb water very rapidly in the initial stage until a saturation level is attained, without further increase in water absorption. The high cellulose content in jute and sisal fibers contribute to more water penetrating the interface

through the micro-cracks induced by swelling of fibers, thus creating swelling stresses leading to composite failure. Thus, the hybridization of both sisal and jute fibers with glass fiber reducing the water absorption content significantly [76].

A B Maslinda et. al. (2017) investigated water absorption behaviors of woven kenaf, woven jute, woven hemp, hybrid interwoven kenaf-jute and kenaf-hemp that prepared by an infusion manufacturing technique using epoxy. Water absorption test was conducted as elucidated in ASTM D570 standard by immersing the composite samples in tap water at room temperature until reaching their water content saturation point. The result showed that the longer exposure to the aqueous environment increased the water uptake of the composites, and Woven kenaf composite had the highest water uptake compared with jute and hemp fiber. As the effect of hybridization, the water uptake of the hybrid composites was lesser than the individual woven composites [77].

Ashik K P. et. al. (2018) Investigated the moisture absorption in normal water, distilled water and sea water and mechanical properties of coconut coir and glass fiber epoxy reinforced hybrid composite. The result showed that incorporation of coconut coir and glass fiber laminate can improve strength and used as an alternate material for glass fiber reinforced composites material. From moisture absorption test result, the graph indicated that the absorption gradually increases with time duration. Then the absorption rate gradually decreases and it remains almost constant. Also, as the coconut % increases automatically the absorption rate also increases [78].

Prem Kuma et.al. (2018) Investigated experimentally mode I fracture toughness in terms of stress intensity factor, and mechanical properties of short banana fiber epoxy reinforced composites using compact tension specimen. It is observed that from the result, the 40 % of banana fiber shows maximum fracture toughness and composite plate of 30% shows the maximum tensile strength. The result showed that increasing the percentage of fiber increases the fracture toughness and tensile strength of the material [79].

Although many studies made on fracture toughness and water absorption behavior of hybrid composite materials, still there is a need to study the fracture toughness and water absorption behavior of hybrid composite materials since natural fibers hybrid composite materials face the problem of crack and water absorption problem. So, analyzing and justifying the effect of the rain water on the fracture behavior of the hybrid composite on the specified loading conditions has been the main task of the research as clearly stated on the section of result and discussion.

Chapter 3: Materials and methods

3.1. Materials

Materials that utilized directly for the manufacturing of the sisal and glass fiber hybrid composite sample are woven sisal fiber [mat form], E-glass fiber, sodium hydroxide, polyester resin with its hardener as well press machine and universal testing machine.

Figure 14: Basic materials

3.1.1. Sisal and extraction process of sisal fibers

From Ethiopian rift valley, sisal plant leaves were collected after cutting at their base from harvest. Initially, for the simplicity of fiber extraction, the leaves trimmed in the longitudinal direction into strips. The fiber extraction will be done manually with the help of a knife. Then the extracted fibers will be washed with pure water to remove dust from the fiber and then dried with sunlight [30, 29].

Figure 15: Extraction of sisal fiber

3.1.2. 5% sodium hydroxide treatment of sisal fiber

The methods for surface modification can be done by physical or chemical treatment according to the way they modify the fiber surface [80]. Chemical treatment of natural fibers is used to remove waxy substances, pectin, lignin, and natural oils from the external surface of the fiber cell wall. Removal of these waxy substances improves the surface adhesion properties for the fiber-matrix interface, fiber's shear strength, rigidity and stiffness, moisture absorption problems, and roughness of the fiber [81].

Ionization of the hydroxy group is done by adding aqueous sodium hydroxide to natural fiber. Sodium hydroxide is the most commonly used chemical for bleaching and cleaning the surface of plant fibers [82]. However, when the percentage of sodium hydroxide increased, fibers' properties is affected by reducing the bonding capacity during the preparation of the composites.

Equation 3.1 shows the chemical reaction that takes place between sisal fiber and aqueous sodium hydroxide solution.

Sisal fiber - OH + NaOH → fiber-O-Na + H_2O …….…. (3.1)

Based on several kinds of literature and a good result from my trial work [i.e., by mixing 1 liter of distilled water with a medium percentage of sodium hydroxide (i.e.,100gm)], 500gm (5%) of NaOH pellet was mixed with 5 liters of distilled water at ambient temperature and soaked for 3hrs for this work. Then the soaked fibers were washed by pure water to get neutral Ph value.

Then, the soaked fibers were washed several times with normal water to purify it from excess NaOH and to get a neutral Ph value, and lastly fibers were allowed to dry in the sunlight for 24 hrs. Since, NaOH can react with air that increases water content (moisture) in the solution, the solution of fibers and NaOH must be kept under a vacuum. Due to this as shown in below figure 16 (b), the container was covered with a plastic sheet in order to create the vacuum inside the bath.

Figure 16: Alkali treatment of sisal fiber

3.1.3. Woven sisal fiber preparation

D. Zhang and Kelkar AD. stated that the woven fabrics textile structures are better than others that are used as reinforcement in composites due to their good mechanical characteristics, conformability, design possibility with different orientations. The formed composite laminates from woven fabrics have good properties in mutually orthogonal directions as well as more balanced properties and better impact resistance than the unidirectional laminates. [43, 83].

Woven fiber composites are two dimensional constructions where the wrap and weft fiber are interlaced into each other to form a layer. The layers are impregnated, stacked in pre-determined orientations, and cured to obtain composite laminates.

During composite lamination material defect such as porosity can be minimized or avoided by degassing of the matrix material or by minimizing fiber bridging. Bridging can be minimized by reducing the percentage in crimp. Because of the interlacement in between wrap and weft yarns a certain amount of waviness is imparted to the wrap and weft yarns of a woven fiber. This waviness is called crimp. Crimp is calculated Eqn. (3.2) by straightening or stretching of the wavy yarns. For getting wrap crimp%, we have to find a difference in between the non-stretched yarn length in fiber and stretched yarn length after removing the yarn from fiber and then divide it by non-stretch yarn length in fiber. Then multiply with 100 for getting wrap crimp in percentage. Crimp can vary from 2% up to 30%.

$$\text{Wrap or Weft crimp (\%)} = \left(\frac{\text{stretched yarn length} - \text{non stretched yarn length)}}{\text{non stretch yarn length}}\right) \text{x } 100 \quad \ldots\ldots\ldots\ldots\ldots 3.2$$

Therefore, even though the tensile strength, absorbency and bridging of composite material increase with the increase in crimp, shrinkage, stiffness and dimensional stability decreases as crimp increases. In that case optimum crimp value can be used to fabricate dimensionally stable and non-porous composite material. Crimp can be related to yarn or thread spacing, GSM (gram per square centimeter) and volume of fiber. Thread spacing is related by Eq. (3.3) and mass of fiber can be related by Eq (3.4).

$$\text{Thread spacing, } p = \frac{\text{non stretched yarn length}}{\text{no of thread}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.3$$

$$\text{GSM} = \frac{\text{ppc } (1+C) \text{ x Yarn count}}{1000} + \frac{\text{epc } (1+Cw) \text{ x Yarn count}}{1000} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.4$$

Where ppc is pick per centimeter, epc is end per centimeter, C is crimp percentage and C_w is wrap crimp in percentage.

Therefore, after the fibers dried, the woven fabric of treated sisal fibers having weft and warp in the perpendicular direction ($0^0/90^0$) was prepared as bi-directional layers. In order to keep the position of the fiber while sewing individual fibers, different materials such as plastic scotch and dimension measuring instruments, etc. are used. The dimension of the woven fabric sample was 38 cm in width and 38 cm in length due to the prepared mold dimension is 40 cm x 40 cm.

Figure 17: Manufactured woven sisal fibers ply

3.1.4. Glass fiber

Commonly E-glass fibers types of fiberglass are found in composites materials and have good combinations of chemical resistance, mechanical and insulating properties. Comparing with other types of glass fibers, E-glass fiber has high resistance to the chemical agents, good electrical insulator characteristic, higher strength and impact resistance, low thermal conductivity, low susceptibility to moisture, and dimensional stability at high temperatures [24]. However, they have also their own disadvantages such as low stiffness, short fatigue life, and highly sensitive to temperature [84]. Due to the mentioned characteristic, E-glass fiber has been taken as a sisal fiber reinforcement for this thesis. Randomly oriented E-glass fiber was procured from world fiber glass and water proofing engineering plc located in Addis Ababa.

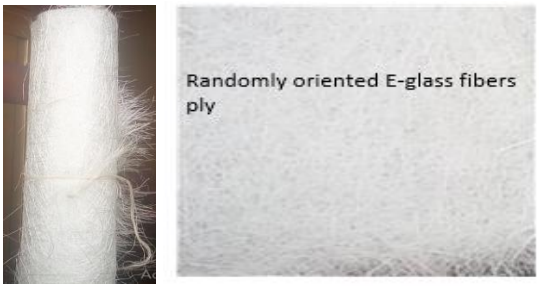


Figure 18: Randomly oriented E-glass fiber ply

3.1.5. Polyester resin

Polyester is polymerizable thermosetting resins types which don't give off reaction product when they cure and have low shrinkage that commonly used in polymer matrix composites. It has good adhesion to other materials, good chemical and environmental resistance, good chemical properties, and insulating properties [85].

Curing temperatures vary from room temperature to approximately 180 °C. The most common curing temperatures range between 120 °C and 180 °C. due to these advantageous properties, the polyester resin was used for this study [86].

Ocpol 711 thixotropic, orthophthalic unsaturated polyester resin was imported from United Arab Emirates by water tank producing company called world fiber glass and water proof engineering located in Addis Ababa.

3.1.5.1. Hardener

Polyester resin is cured by adding a hardener, which causes a chemical reaction without changing its own composition and increases the polymerization process. It initiates the chemical reaction of polyester resin and monomer ingredients from liquid to solid states. Resin and hardener should be mixed evenly to obtain better bonding and curing. The most favorable proportion of polyester and hardener mixture is 10:1. Finally, these proper amounts of polyester and hardener are mixed and stirred for a few minutes using deep stick material.

3.2. Hybrid composite specimen preparation method

Before reinforcement of sisal fiber with glass fiber, sisal fibers were chemically treated in order to enhance its property. Next fibers volume fraction and matrix volume fraction of the hybrid composite are determined. Before composite laminate is fabricated, ply thickness and ply stacking sequence of the laminated hybrid composite structure is designed. Even if, composite materials can be prepared by different techniques, the sisal and glass fiber hybrid composite was using hand lay-up techniques due to some factors such as familiarity with technique, availability of tools, cost.

3.2.1. Fiber and matrix volume content of the composites

The first and the critical task in fabrication, and analysis of hybrid composite materials is the determination of ingredient percentages such as fiber and matrix fraction presence in laminate.

Properties of hybrid composite laminate elements are determined and limited by values of fibers and matrix fraction presence [87].

In general, the results obtained from the equations presented below are mandatory for composite laminate preparation, to determine the size of laminates, and to use ASTM standards. some basic assumptions in fiber-reinforced hybrid composites are perfect bonding between fibers and matrix, uniformity of fibers throughout the matrix, the matrix should be free of voids, the applied load is either parallel or normal to fiber direction, initially, the lamina is stress-free states, and fibers and matrix behave as linear elastic materials [88].

A. Fiber and matrix weight fraction [W_F, W_M]

1. Fiber weight fraction = $\frac{\text{Weight } of\ fiber}{\text{Total weight}}$, $W_F = \frac{Wf}{Wf+Wm}$ …….…… (3.5)

2. Matrix weight fraction = $\frac{\text{Weight } of\ matrix}{\text{Total weight}}$, $W_M = \frac{Wm}{Wf+Wm}$ ……. (3.6)

3. Total weight of composite = weight of fibers and weight of matrix, $W_c = W_f + W_m$ …. (3.7)

B. Fiber and matrix volume fraction [V_F, V_M]

1. Volume of fibers = $\frac{\text{Weight of fiber}}{\text{Density of fiber}}$, $V_f = \frac{Wf}{\rho f}$ ……...……... (3.8)

2. Volume of matrix = $\frac{\text{Weight of matrix}}{\text{Density of matrix}}$, $V_m = \frac{Wm}{\rho m}$ ……... (3.9)

3. Volume of composite = Volume of fibers + Volume of matrix, $V_f + V_m = V_c$……. (3.10)

4. Fiber volume fraction (V_F), $V_F = \frac{\text{volume of fiber}}{\text{Total volume}} = \frac{Vf}{Vf+Vm} = \frac{Vf}{Vc}$ …….……..... (3.11)

5. Matrix volume fraction (V_M), $V_M = \frac{\text{volume of matrix}}{\text{Total volume}} = \frac{Vm}{Vf+Vm} = \frac{Vm}{Vc}$ …… …..….. (3.12)

C. Mass density of ply [ρ_c]

Applying the definition of volume fraction of density of composite (ρ_c) can be expressed as in terms of fiber density (ρ_f) and matrix density (ρ_m):

$$\rho_c = \frac{\text{Total weight}}{\text{Total volume}} = \frac{\text{Weight of fibers}}{\text{Total volume}} + \frac{\text{Weight of matrx}}{\text{Total volume}}$$

$$\rho_c = \frac{\text{volume of fiber}}{\text{Total volume}} * \rho_f + \frac{\text{volume of matrx}}{\text{Total volume}} * \rho_m,\ \rho_c = \rho_f V_F + \rho_m V_M \text{.....} \quad (3.13)$$

D. Ply thickness [h]

The thickness of ply is defined as the number of grams of mass of fibers (W_f) per m^2 of area. The ply thickness, denoted as b, is such that:

$$b*1(m^2) = \text{Total volume} = \text{Total volume x } \frac{\text{mof}}{\text{fiber volme x } \rho f}, \quad b = \frac{\text{total volume}}{1(m^2)} \quad \ldots\ldots\ldots\ldots\ldots\ldots (3.14)$$

Here, $W_f = W_{\text{sisal fiber}} + W_{\text{E-glass fiber}}$

Where:

W_f: weight of fiber (g)
W_m: weight of matrix (g)
W_c: weight of composite specimen (g)
ρ_f: density of fiber (g/cm^3)
ρ_c: density of composite specimen (g/cm^3)
V_c: volume of composite specimen (cm^3)
h: ply thickness (mm)

W_F: fiber weight fraction
W_M: matrix weight fraction
V_f: volume of fibers (cm^3)
ρ_m: density of matrix (g/cm^3)
Vm: volume of matrix(cm^3)
V_M: matrix volume fraction
V_F: fibers volume fraction

Here, fibers are sum of fiber glass and sisal fibers. In this study, primary data's (fibers density and matrix densities) about E-glass and sisal fiber and polyester resin are taken from literature reviews. The calculated results are obtained from primary data's using the rule of mixtures formula's shown above in 3.2.1 subtitled. By using the above-mentioned equations, the values are evaluated and presented in the table 1.

Table 1: Table fibers and matrix volume values

Primary data		**Calculated Results**	
Parameters	Value	Parameters	Value
Sisal fiber ply weight ($W_{f\text{-sisal}}$)	71.25 g	Sisal fiber volume ($V_{f\text{- sisal}}$)	53.6 cm^3
Glass fiber ply weight ($W_{f\text{-glass}}$)	171.05 g	Glass fiber volume ($V_{f\text{- glass}}$)	66.6 cm^3
Total fiber weight	242.3 g	Total fiber volume	120.2 cm^3
Sisal fiber density ($\rho_{f\text{-sisal}}$)	1.33 g/cm^3	Matrix volume (V_m)	121.5 cm^3
Glass fiber density ($\rho_{f\text{ -glass}}$)	2.57 g/cm^3	Total fiber volume ratio (V_F)	50 %
Matrix weight (W_m)	145.8 g	Matrix volume ratio (V_M)	50 %
Matrix density (ρ_m)	1.2 g/cm^3	Total fiber weight ratio (W_F)	62.4 %
		Matrix weight ratio (W_M)	37.6 %
Ply thickness		Woven sisal fibers ply thickness	0.35 mm
		Randomly oriented E-glass fibers ply thickness	0.25 mm

3.2.2. Hand lay-up techniques

Hand lay-up fabrication techniques were adapted to fill up the prepared mold with an appropriate amount of polyester resin mixture, glass fiber ply, and woven sisal fiber ply, such that starting and ending with layers of resin. The quantity of catalyst added to resin at room temperature for curing was 1% by volume of resin each.

The advantages of hand lay-up techniques are low capital investment, simple process, and versatility. However, it is mostly labor-intensive [89]. Mold release is essential for preventing the matrix from sticking to the mold when the composite is apart. The most common type of release agent used for this thesis work is paste wax (oil). Better surface finish is obtained with the use of paste wax. Usually paste wax is quick, cheap, and widely available.

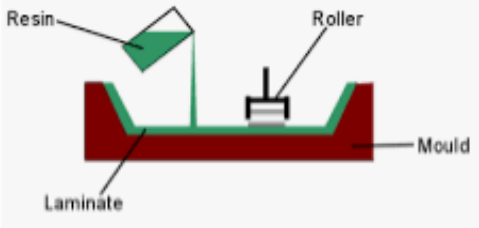


Figure 19: Hand lay-up method

3.2.3. Hybrid composite plies and laminates design

Based on the reinforcement, matrix, and curing process, the components architecture of bidirectional woven sisal and E-glass reinforced polyester hybrid composite has been defined as glass-sisal-sisal-sisal-sisal-glass. In this arrangement, the outer part of the hybrid was enclosed by E-glass fiber plies to minimize the water absorption problem of sisal fibers composite materials since glass fibers have better resistance to water absorption. Four plies of woven sisal fibers are fabricated and two plies of randomly oriented E-glass fibers prepared for 2mm thick hybrid specimen. For 5mm thick hybrid specimen, ten plies of sisal fibers fabricated and two plies of E-glass fibers used with same plies arrangement of 2mm thick hybrid specimen.

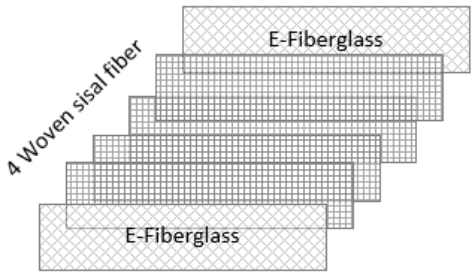


Figure 20: Hybrid plies configuration

3.2.4. Hybrid composite manufacturing process and steps

Polyester resin mixed with a hardener to prepare the composite plate. The weight ratio for mixing polyester and hardener is 10:1. The mixer is strewed with a stirrer in a mixing container (bowl) for about one minute continuously. The mixing process is done slowly to entrain any excess air bubbles in the resin. After all the materials are prepared, the workstation is ready and mold preparation is done. The hand lay-up process can be started. First of all, the overall mold surface was painted with mold releaser (paste wax), then some mixture of polyester resin and hardener is dropped in the mold, and a brush or roller is used to spread it around all mold surfaces.

Next woven sisal fiber ply and glass fiber ply have been arranged on the mold surface according to their specific stacking sequences. Then, the first fibers ply is then laid. This layer is wetted with resin and then softly press using a roller to make the resin that was added in. Especial care was taken to eliminate all air bubbles as much as possible by rolling a small hand rolling tool that is repeated until the wanted thickness is achieved. At the last, press the mold on the hydraulic press machine with compression pressure of 100 bar (10 MPa) and left for 12 hours at room temperature for consolidation. The air gaps between the fibers and resin squeezed out and excess resin is removed and the sample dried by pressing the sample with the help of a hydraulic press machine. After the specified time we put out the mold from the hydraulic press machine. In short, figure 21 shows specimen fabrication process flow chart.

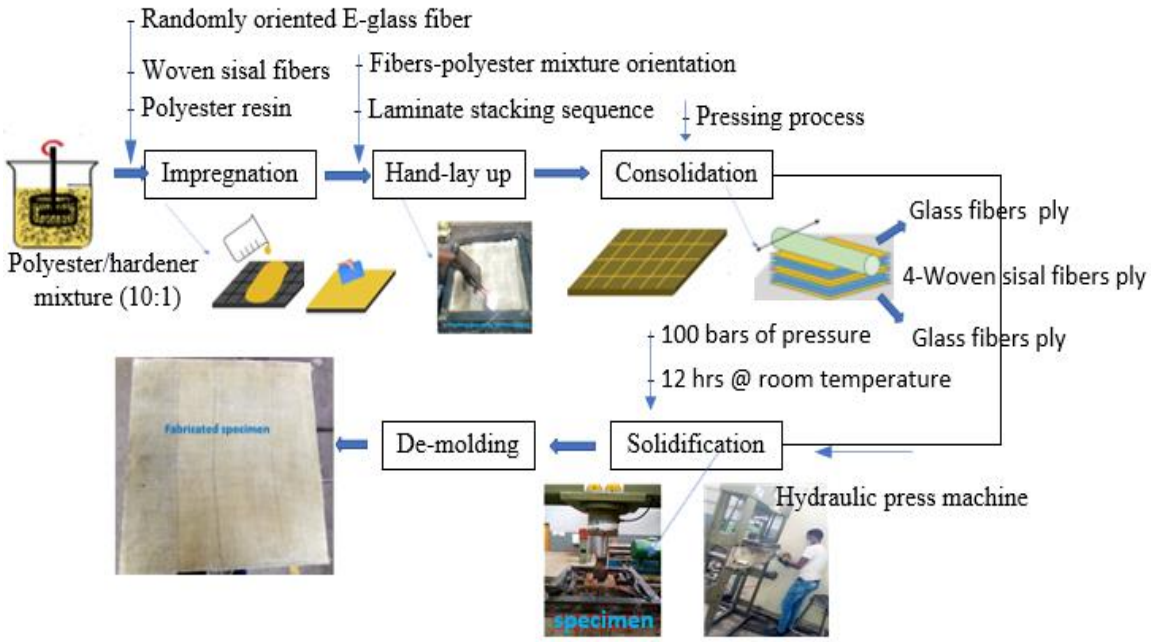


Figure 21: Specimen fabrication process flow chart @ AAiT, basic mechanical workshop

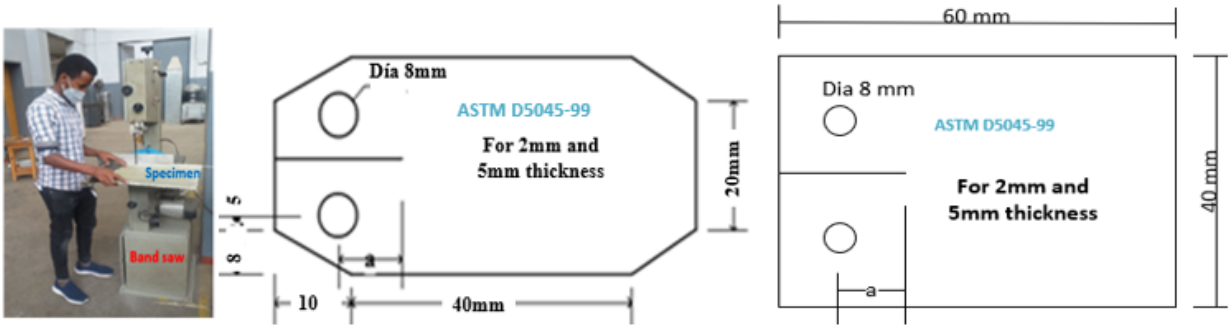
In this paper work, total 15 test hybrid specimen prepared for fracture toughness, and moisture absorption tests, for each test 5 specimens, with appropriate ASTM standards using a band saw as shown in figure 21.

3.3. Experimental setup and testing conditions

3.3.1. Band saw, ASTM standards for dimensions

The prepared hybrid composite specimen cut using a band saw into the desired dimension based on the respective standards for compact tension test and moisture absorption that have been performed using a universal testing machine.

For both thickness (2mm and 5mm), the appropriate American society of testing materials standards ASTM D5045-99 and ASTM D5229-92 was followed while preparing the compact tension specimen of doubly-tapered (chamfered), rectangular configurations and moisture absorption test specimens respectively for woven sisal and glass fibers reinforced polyester hybrid composite material test specimen and these samples dimensions and configurations are shown as in figure 22.



A) Specimen cutting, B) Doubly-tapered (chamfered) and C) Rectangular CT test specimens

Figure 22: Specimen's dimension and configuration as per ASTM D5045-99

N. Blanco et. al. (2014), among CT specimen geometry configurations of extended CT, widened CT, Tapered CT, and doubly-tapered, the CT specimen geometry that best ensures crack propagation for fracture toughness characterization of woven laminated composite material is the doubly-tapered CT specimen geometry that showed lower values for the failure indices [90]. Therefore, doubly-tapered and rectangular CT specimen geometry was selected for this thesis work.

3.3.2. Universal testing machine

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

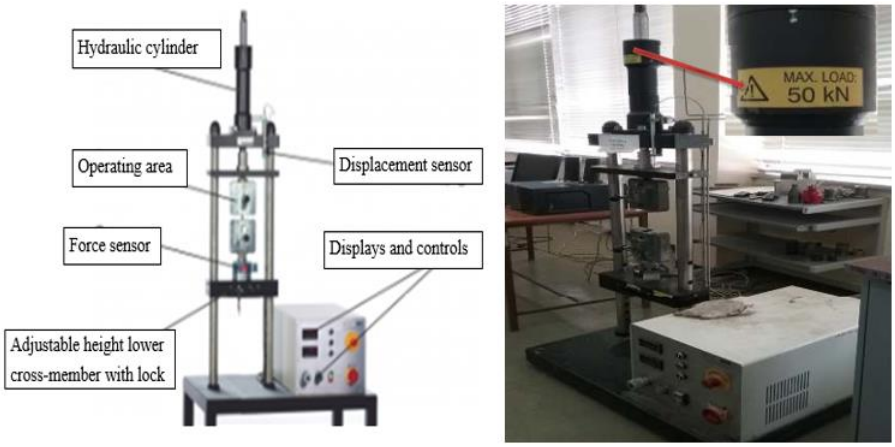


Figure 23: Universal testing machine

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

Specimen of compact tension was prepared for 0.5 ratio value between crack length, 'a' and crack width, 'w' (a/w = 0.5). All dimensions are as per ASTM D5045-99 standard and crack thickness (crack opening) is the thickness of band saw blade thickness. For each test, 5 compact tension specimens were prepared and tested using universal testing machine with cross-head speed of 6 mm/sec at the room temperature. load and load line displacement were recorded from the given test and critical stress intensity factor calculated for the recorded loads. The typical prepared 2mm and 5mm compact tension test specimens are shown in figure 24.

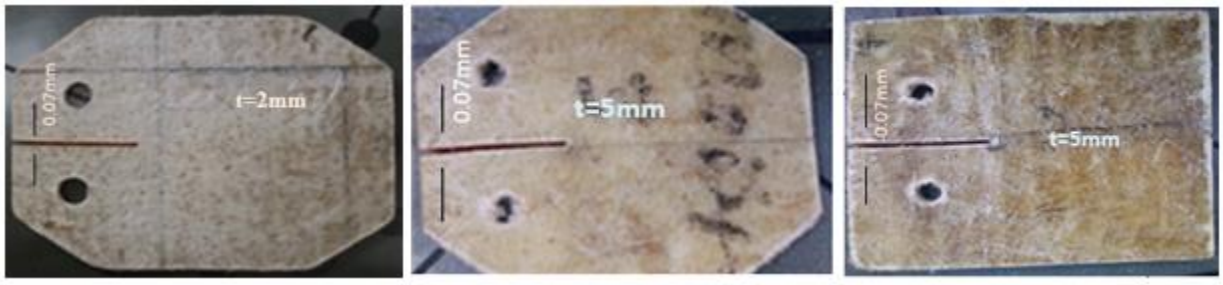


Figure 24: Prepared compact tension test specimen's configurations

3.3.2.3. Water absorption test (ASTM D5229 -92)

The water absorption tests of woven sisal and glass fiber reinforced polyester composite materials were carried out through immersion in rain water. The rain water was selected to check performance and applications of manufactured hybrid material in real-life conditions such as in rainy conditions and humid environment. The specimens were taken out and after wiping out the water from specimens, specimens were weighed regularly using a precise electronic balance to find out the content of water absorbed at an interval of 24 hr. for 1 week. The percent of water absorption content is calculated by the weight differences from Eqn. 3.12 using (ASTM D5229M-92):

$$\text{Water absorption content, M, (\%)} = \frac{W2-W1}{W1} \text{ x } 100 \quad \text{..... 3.15}$$

Where W_2 and W_1 mass of moist specimen after immersion and mass of dry specimen before immersion respectively.

Moisture diffusivity constant, Dz, is the property of a material that describes the rate at which the material absorbs or desorbs moisture that is calculated as follows:

$$\text{Diffusivity constant=} D_z = \left(\frac{h}{4Mm}\right)^2 \left(\frac{M2-M1}{\sqrt{t2}-\sqrt{t1}}\right)^2 \quad \text{..... 3.16}$$

Where, D_z = moisture diffusivity constant, h = average specimen thickness, Mm = effective moisture equilibrium content, % and $\frac{M2-M1}{\sqrt{t2}-\sqrt{t1}}$ = slope of moisture absorption plot in the initial linear portion of the curve, $\sqrt{seconds}^{-1}$. Fickian diffusion for materials moisture absorption and desorption that follows Fick's second law.

It must be a single-phase Fickian material, a material that behaves according to Fick's law:

$$\text{Fickian diffusion=} \frac{\partial c}{\partial t} = D_z \left(\frac{\partial^2 c}{\partial z^2}\right) \quad \text{..... 3.17}$$

Where, c = specimen moisture concentration, g/mm^3, t = time, s, $\frac{\partial c}{\partial t}$ = time rate of change of moisture concentration, g/mm$^{3/}$s, Dz = Fickian material diffusion constant through-the thickness of the material, mm^2/s, and z = through-the-thickness direction, mm.

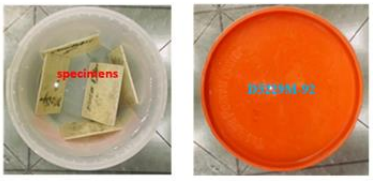


Figure 25: Hybrid specimen immersion in rainy water *[91]*

Table 2: Weight of the specimen before and after soaking (2mm thickness)

Properties		Hybrid specimen with 2mm thickness						
Original weight of composite specimen (g)			Weight of composite specimen (g), after soaking in rain water					
Dry specimen		Wet specimen per 24hr.						
		After 24hr.	After 48hr.	After 72hr.	After 96hr.	After 120hr.	After 144hr.	After 168hr.
Specimen -1	8.3	8.301	8.3042	8.3044	8.304412	8.304436	8.304445	8.304447
Specimen -2	8.2	8.201	8.2041	8.2043	8.20431	8.204322	8.204331	8.204334
Specimen -3	8.4	8.401	8.4042	8.4046	8.404613	8.404623	8.404632	8.404635
Specimen-4	8.2	8.201	8.2041	9.2043	8.204311	8.204335	8.204344	8.204347
Specimen -5	8.2	8.2012	8.2043	8.2045	8.204513	8.204537	8.204546	8.204549
Average	8.24	8.26104	8.26418	8.26442	8.264432	8.264451	8.26446	8.264462

Table 3:Weight of the specimen before and after soaking (5 mm thickness)

Properties		Hybrid specimen with 5mm thickness						
Original weight of composite specimen (g)			Weight of composite specimen (g), after soaking in rain water					
Dry specimen		Wet specimen per 24hr.						
		After 24hr.	After. 48hr.	After 72hr.	After 96hr.	After 120hr.	After 144hr.	After 168hr.
Specimen-1	18.2	18.201	18.2058	18.20582	18.20585	18.20586	18.20587	18.20589
Specimen -2	18.1	18.102	18.1064	18.10641	18.10643	18.10644	18.106446	18.106447
Specimen -3	18.1	18.102	18.1061	18.10634	18.10631	18.10633	18.10635	18.10637
Specimen -4	18.1	18.101	18.1063	18.10632	18.10634	18.10636	18.10638	18.10639
Specimen -5	18.1	18.102	18.1061	18.10613	18.10615	18.10617	18.10619	18.1062
Average	18.12	18.1216	18.1214	18.1262	18.12622	18.12623	18.12625	18.12626

This the tabulated data in table 2 and 3 are the weights of hybrid specimen before and after soaking in rain water. Using this calculated data as input data, water absorption behavior of hybrid specimen determined.

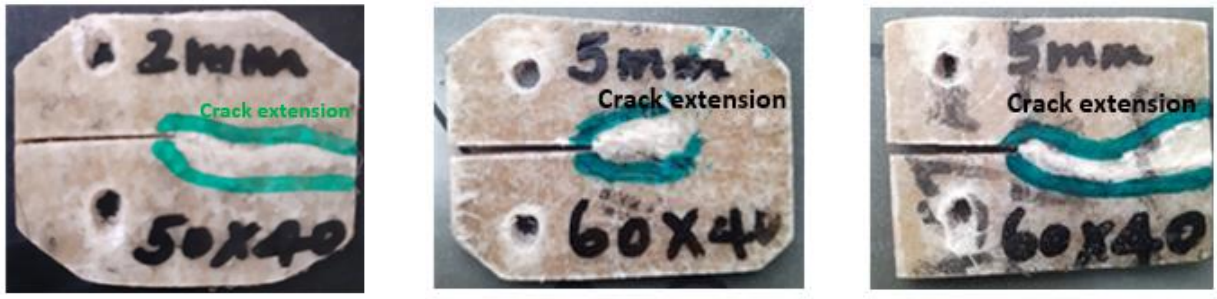
Chapter 4: Experimental results and discussions

4.1. Mode I fracture toughness tests results

Five test samples were prepared from woven sisal and E-glass fibers hybrid composite for compact tension test. Experimental results of these specific tests have been summarized using graphs, which can relate different material properties that are used in fracture mechanics to show fracture resistant of a given composite material, including critical stress intensity factor and strain energy release rate before and after aging for 7 days in rainy water.

In this experimental work, loading and load advancement, crack length and crack advancement recorded automatically from software that integrated with universal testing machine.

Tested specimens result of 2mm and 5mm thickness before aging in rain water



Tested samples result of 5 mm thickness after aging in rain water

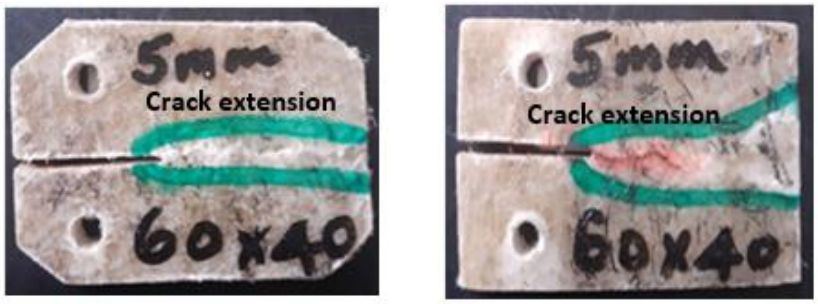


Figure 26: Compact tension test results before and after aged in rain water

4.1.1. Stress intensity factor and strain energy release rate

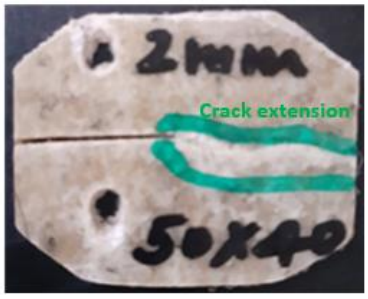
The stress intensity factor of the compact tension specimen was computed according to ASTM D5045-99. Crack and load advancement generated by software and K_{IC} or S_{IF} calculated as per ASTM D5045-99 standard. $K_{IC} = \frac{p}{h\sqrt{w}} f(a/w)$ ……..…… 4.1

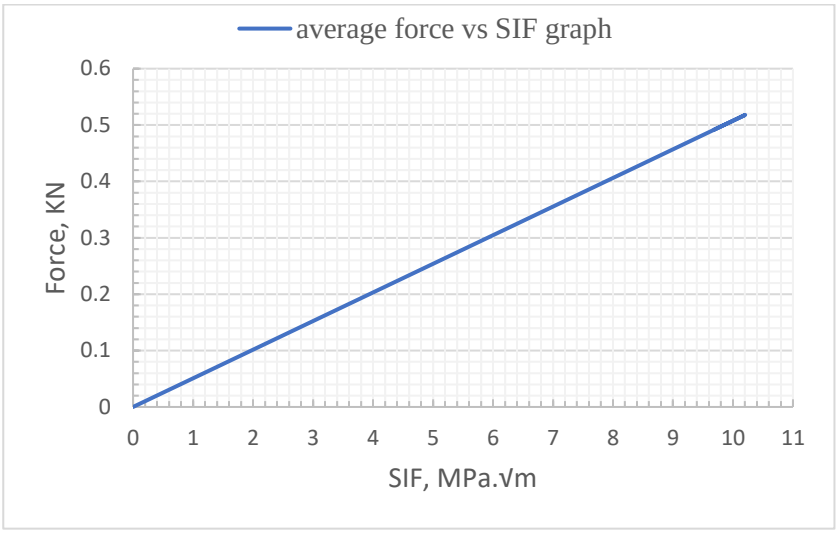
Where: K_{IC} is critical stress intensity factor, p is applied load, h and w are hybrid specimen thickness and width respectively, f(a/w=0.5) is geometry factor taken from standard.

The critical strain energy release rates were also computed with compliance calibration method, which employs the concept of compliance as the ratio of deformation to applied load.

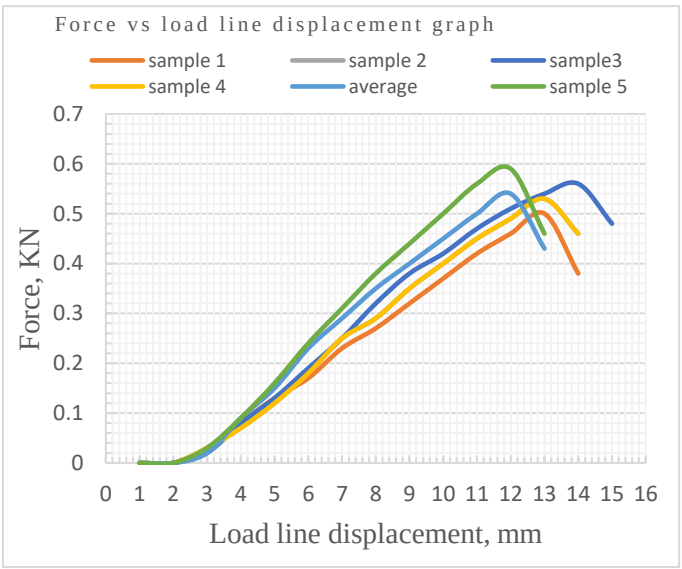
The results are shown in the following graphs:

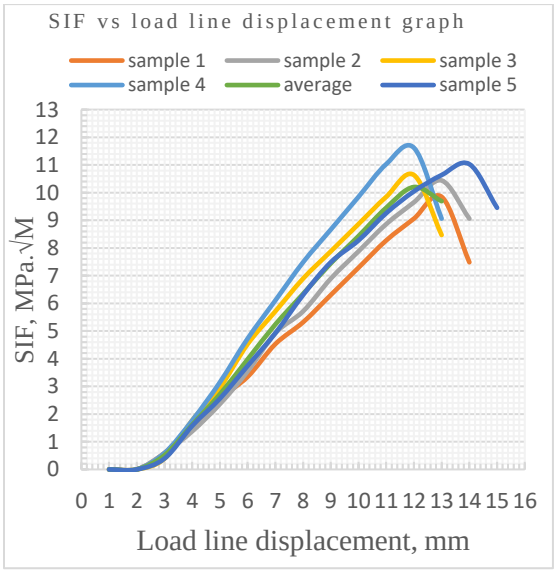
1. For doubly-tapered (chamfered), 2mm thickness compact tension specimens





a) Force vs stress intensity factor

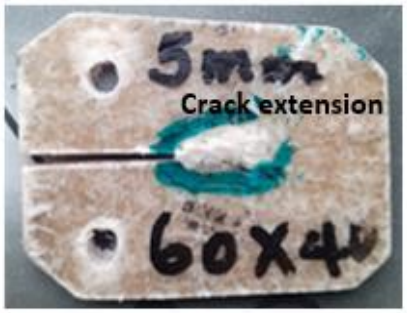


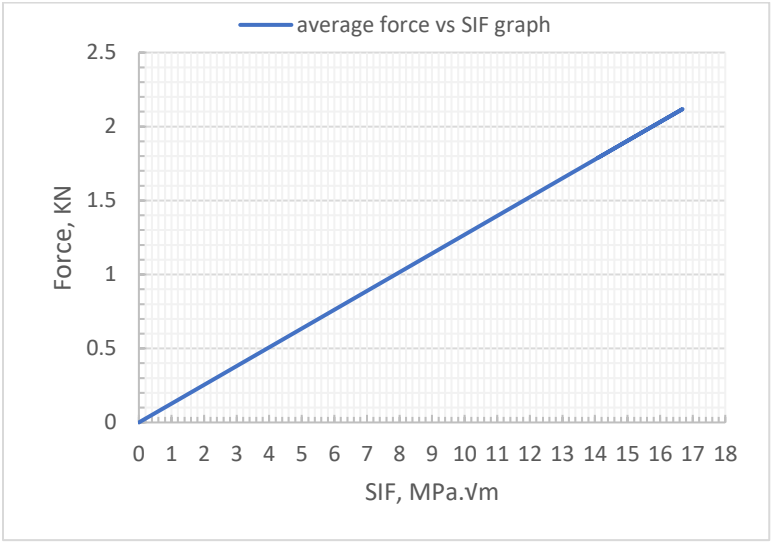


b) Force vs load line displacement c) Stress intensity factor vs load line displacement

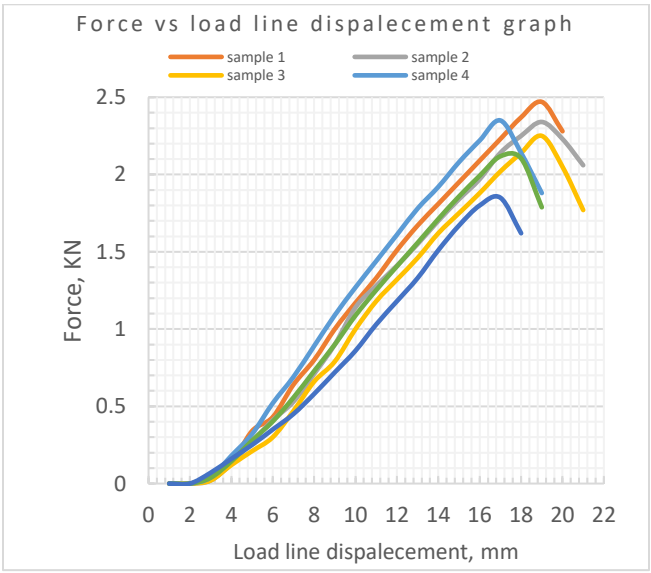
Figure 27: Doubly-tapered (Chamfered 2mm thick) compact tension test results

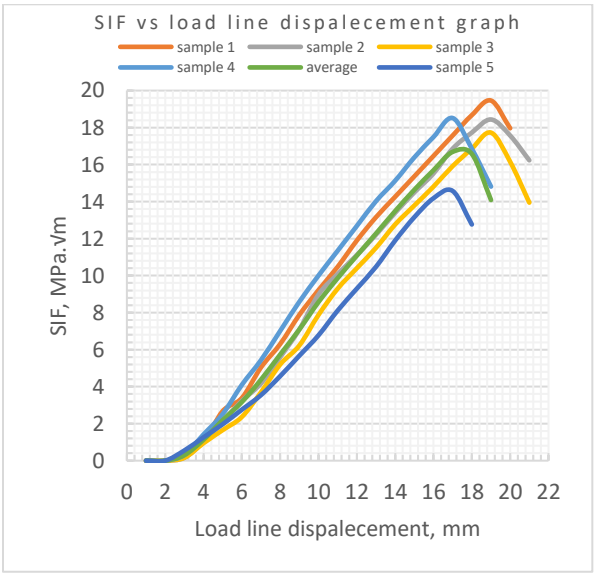
2. For doubly-tapered (chamfered), 5mm thickness compact tension specimens





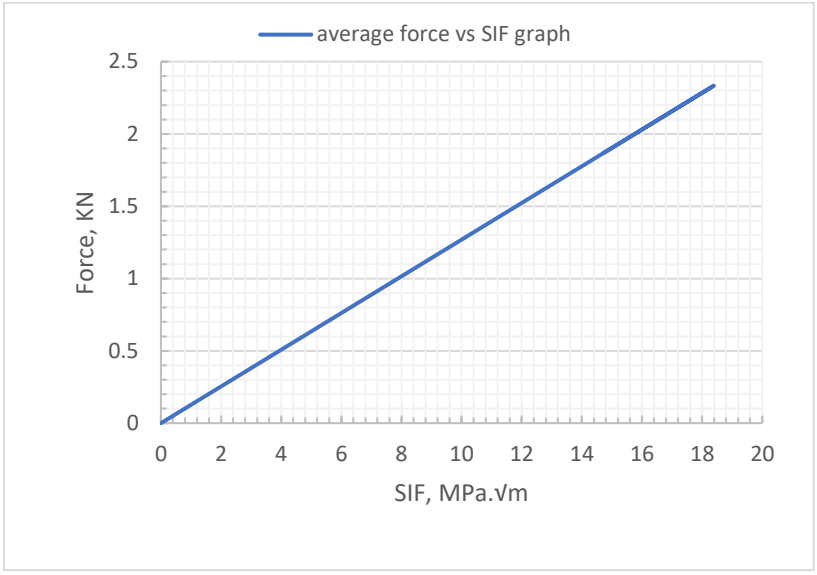
a) Force vs stress intensity factor



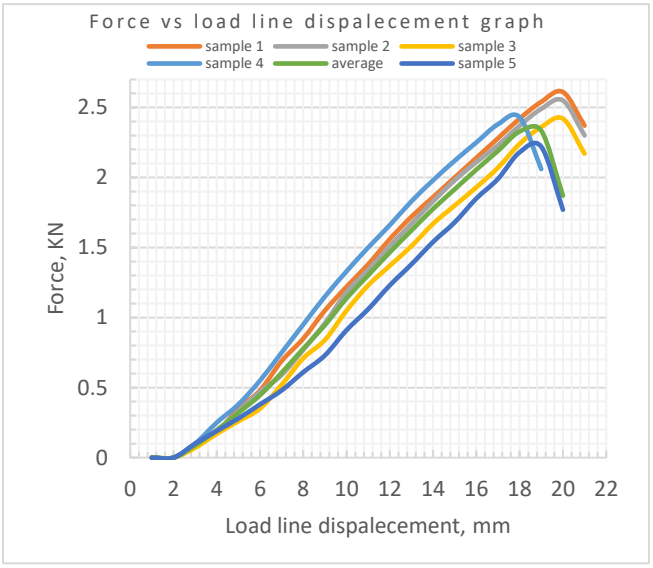


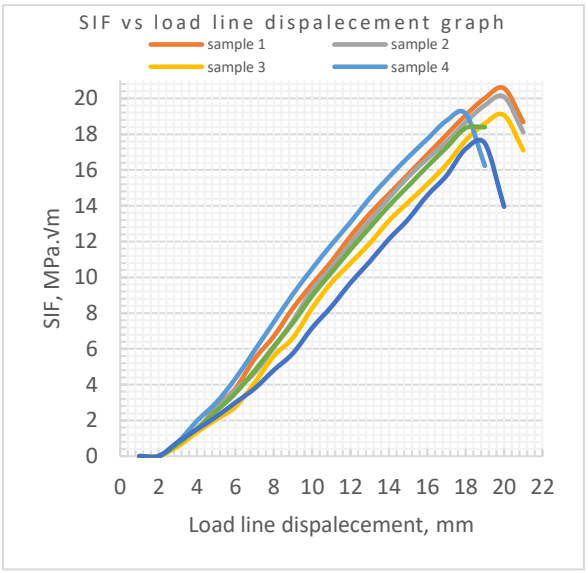
b) Force vs load line displacement c) Stress intensity factor vs load line displacement

3. For rectangular (5mm thickness) compact tension specimens



a) Force vs stress intensity factor





b) Force vs load line displacement c) Stress intensity factor vs load line displacement

Figure 28: Rectangular (5mm) compact tension test results

As shown from the experimental result and analysis, the average of critical stress intensity factor and critical strain energy release rate (G_{IC}) of specimens summarized by table 4 as shown from result graphs.

Table 4: Fracture toughness result comparison in terms of geometry and thickness

Material	Specimen geometry	Thickness	Average					
			Crack extension	Max. force	Fracture toughness			
					K_{IC} (MPa.√m)	Standard Deviation	G_{IC} (KJ/m²)	Standard Deviation
SGHC-Compact tension	Chamfered	2mm	7.54mm	0.518KN	10.2	0.662	7.85	0.648
	Chamfered	5mm	10.65mm	2.118KN	16.68	1.874	12.74	0.913
	Rectangular		11.55mm	2.328KN	18.34	1.301	13.57	1.485

The results of the experimental work showed that, the mode I fracture toughness value of K_{IC} =10.2 MPa. √m and K_{IC} =16.68 MPa. √m respectively for 2mm and 5mm chamfered specimen thickness, which is resulted in the normal specimen test.

4.2. Rain water absorption tests result

Rain water was selected to test water absorption effect on fracture toughness of hybrid in real-life conditions such as in rainy condition and humid environment. Shown as in figure 29 and 31, the percentage of rain water absorption curve is plotted against the square root of the immersion time the manufactured hybrid composite specimen. The rain water absorption test result of rectangular specimens with 2mm and 5mm thickness tests has been summarized using graphs, which shows that the performance of the materials in rainy water or humid environments.

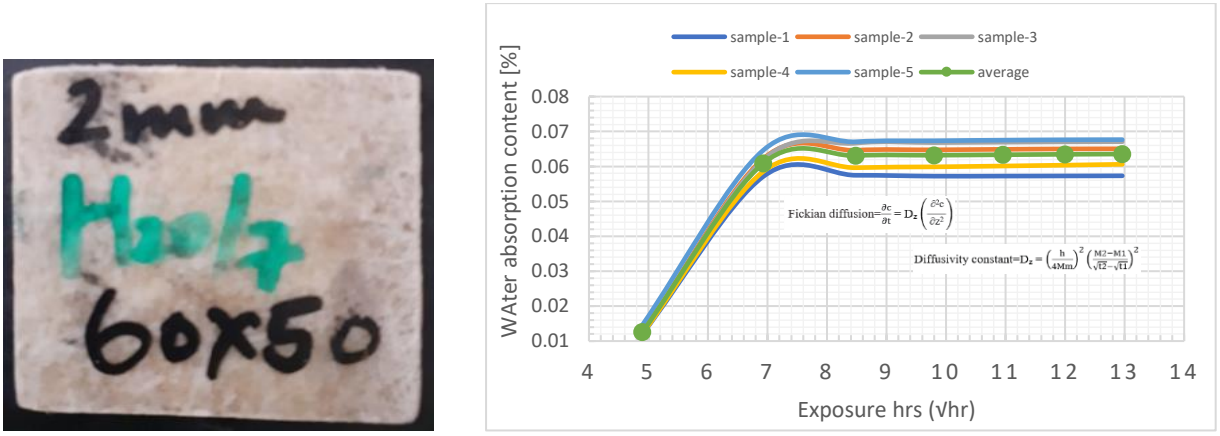


Figure 29: Rain water absorption content (%) for 2mm thickness hybrid

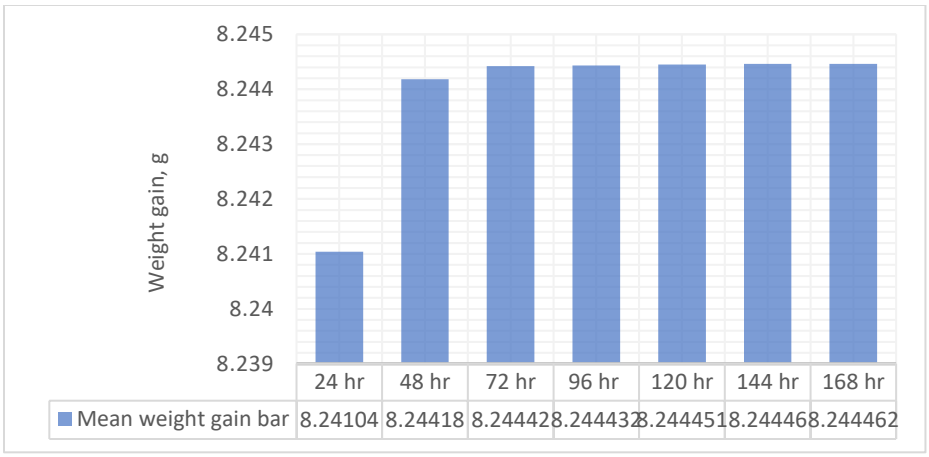


Figure 30: Weight gain of 2mm thickness hybrid

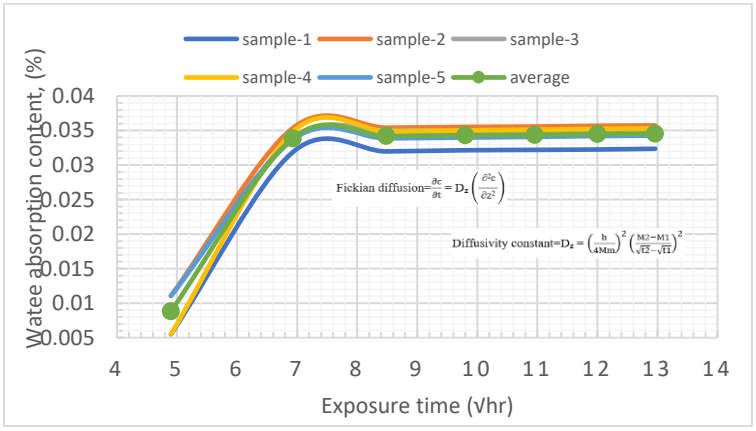


Figure 31: Rain water absorption content (%) for 5mm thickness hybrid

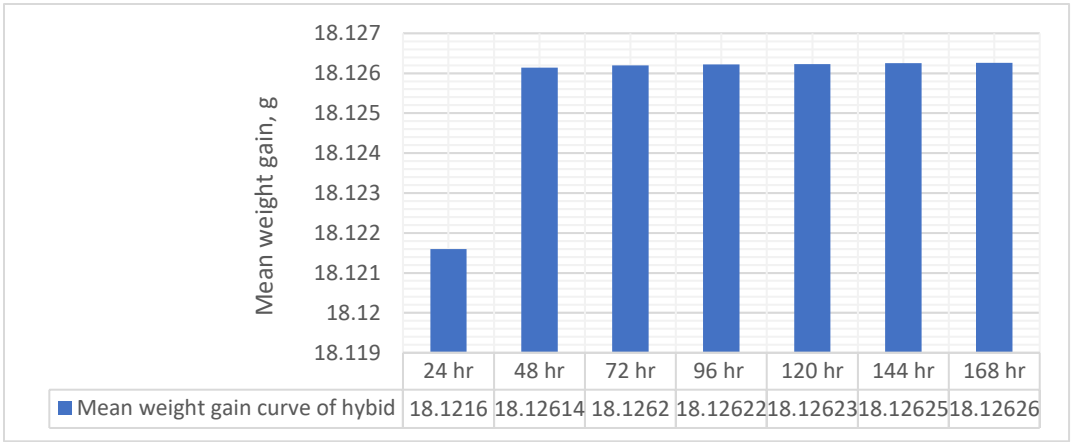


Figure 32: Weight gain of 5mm thickness hybrid

As shown in figure 29 and 31, the manufactured hybrid composite specimen of each thickness absorbs rain water in the initial stage until the saturation level is attained without rain water absorption and a linear section at the start of the curve is indicative of fickian diffusion.

Table 5: Rain water absorption content results comparison in terms of thickness

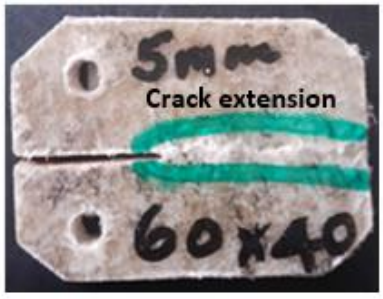
Material	Specimen thickness	Duration of exposure (days)	Maximum water absorption content (%)	Diffusivity (mm^2/s)
SGHC	2mm	7	0.063099	6.26501E-08
	5mm		0.034238	6.09811E-10

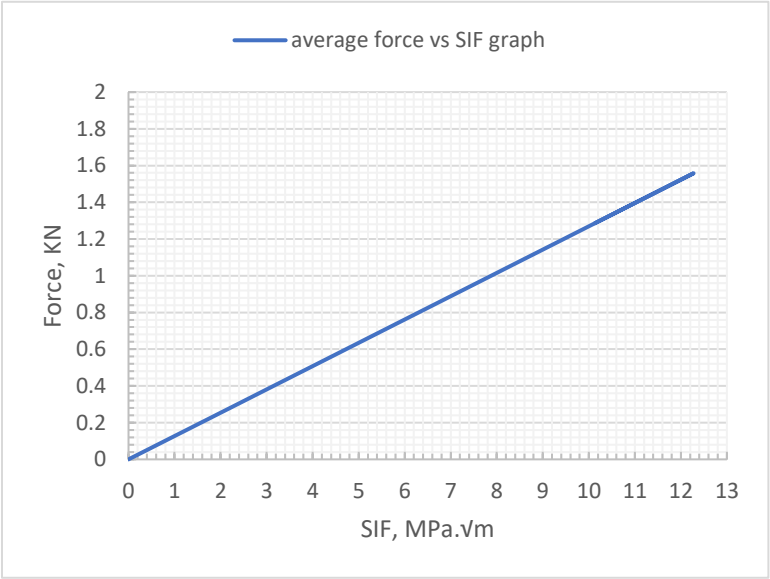
The water absorption tests were carried out through immersion in rain water for 7 days and the maximum water absorption of the hybrid specimen was 0.063% and 0.034% respectively for 2mm and 5mm thickness. As shown from the result, as the thickness of hybrid specimen increases, the rain water absorption content and diffusivity behaviors of the hybrid specimen minimized. Generally, the result shows that the performance and applications of the woven sisal-glass hybrid composite materials in rainy, water or humid environments.

4.2.1. Effect of rain water absorption on the fracture toughness

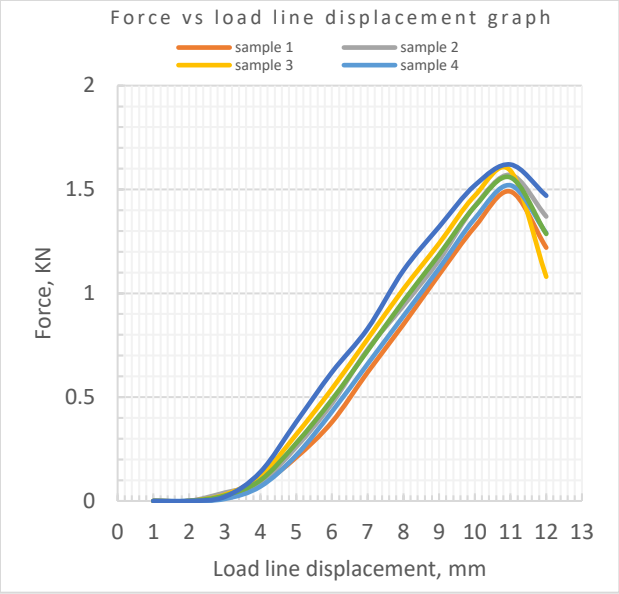
To determine the effect of rain water absorption on the fracture toughness of manufactured specimen, specimen immersed in rain water for 1 week. After aging (immersing) 5mm thickness specimen in rain water for 7 days, the following fracture toughness results are shown by graphs.

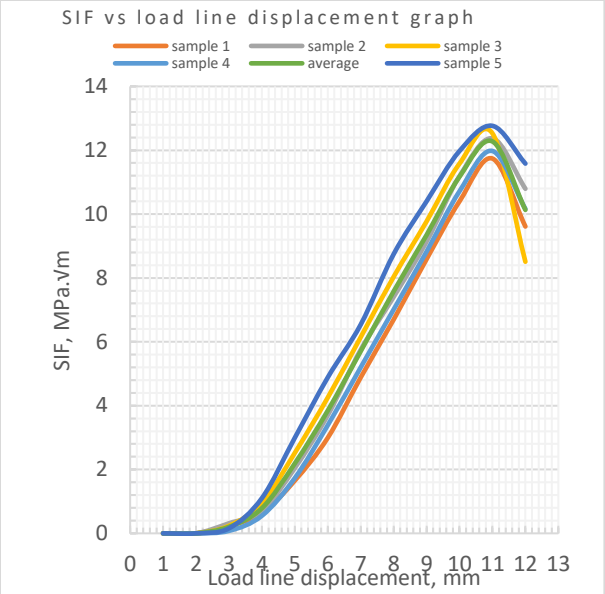
1. For doubly-tapered (chamfered), 5mm thickness compact tension specimens





a) Force vs stress intensity factor

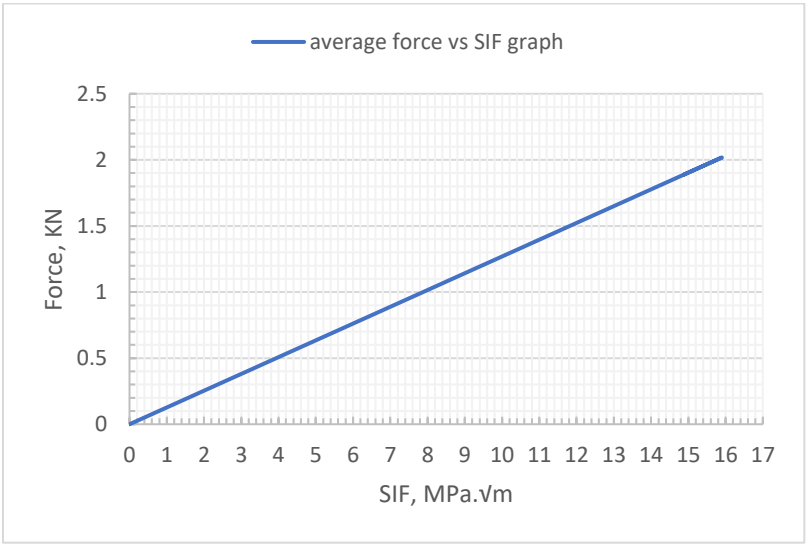




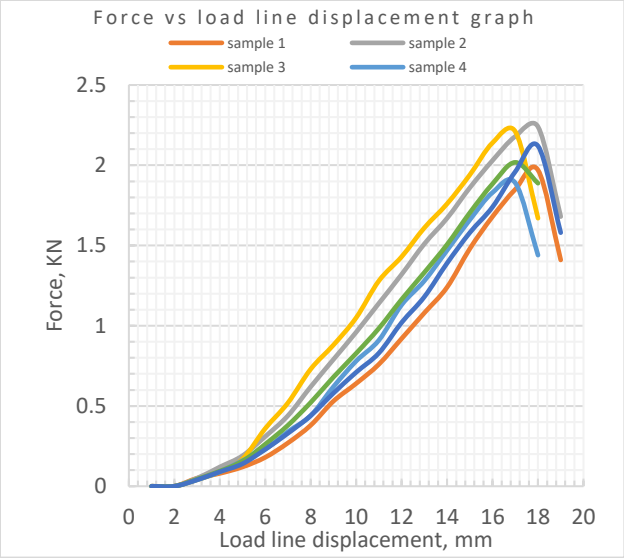
b) Force vs load line displacement

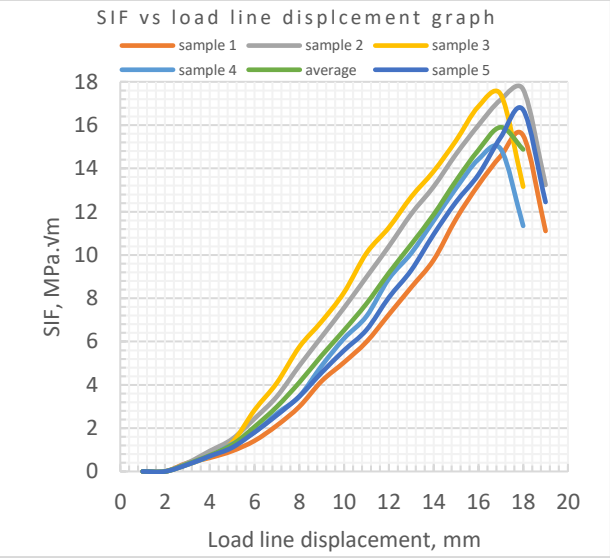
c) Stress intensity factor vs load line displacement

2. For rectangular 5mm thickness compact tension specimens



a) Force vs stress intensity factor





b) Force vs load line displacement c) Stress intensity factor vs load line displacement

Table 6: Effect of rain water absorption on fracture toughness hybrid composite

Material	Specimen geometry	Thickness	Average					
			Crack extension	Max. force	Fracture toughness			
					K_{IC} (MPa.√m)	Standard Deviation	G_{IC} (KJ/m²)	Standard Deviation
SGHC-Compact tension	Chamfered	5mm	6.378mm	1.558KN	12.27	0.414	10.4	1.519
	Rectangular		11.01mm	2.018KN	15.9	1.195	11.28	1.733

Table 7: K_{IC} comparisons of manufactured hybrid with and without rain water absorption

Material	Specimen geometry	Thickness	Average			
			Fracture toughness			
			Without water absorption		With water absorption	
			K_{IC} (MPa.√m)	G_{IC} (KJ/m²)	K_{IC} (MPa.√m)	G_{IC} (KJ/m²)
Hybrid specimen	Chamfered	5mm	16.68	12.74	12.27	10.4
	Rectangular		18.34	13.57	15.9	11.28

Therefore, as shown from table 8, rain water absorption has negative effect on fracture toughness of the hybrid composite material and fracture toughness decreased by 3.94 MPa. √m. due to the specimen immersion in rain water for one week as shown from table 7.

4.3. Discussion

The experimental work showed that, the mode I fracture toughness value of K_{IC} =10.2 MPa. √m and K_{IC} =16.68 MPa. √m respectively for 2mm and 5mm specimen thickness, which is resulted in the normal specimen test. The rain water absorption tests were carried out through immersion in rain water for 7 days and the maximum rain water absorption of the hybrid specimen was 0.063% and 0.034% respectively for 2mm and 5mm thickness. Also, due to rain water aging of the hybrid specimen of 5mm thickness for 7 days in rain water, the fracture toughness value of the hybrid specimen was decreased by 3.94 MPa. √m. The fracture toughness of rain water exposed specimens are lower compared to the normal specimens in a compact tension test.

From all the tested specimens, it was seen that specimen's failure that propagate from the initially created crack on the mid plane under mode I loading conditions. This failure which goes out of the initially cracked plane was also observed on specimens immersed in rainy water. The reason behind these failure modes is not identified but it seems due to the cause of the gripping mechanisms alignment's and absorbed rain water sensitivity.

Figure 33: Failure modes in compact tension tested specimen

Chapter 5: Conclusion and recommendation

5.1. Conclusion

The accomplished experimental work describes fracture toughness and the influence of rain water aging on the fracture toughness of compact tension specimens made from woven sisal fibers ply and E-glass fibers ply reinforced with polyester resin hybrid composite under mode I loading conditions. The procedures followed ASTM standards and results were obtained accordingly.

Studying the fracture toughness of woven sisal fibers ply and E-glass fibers ply reinforced with polyester resin hybrid composite under rain water exposure condition by comparing it with the normal condition specimens is useful for designing and setting preconditions for engineering applications in water or humid environments.

In general, the accomplished experimental work presented here showed quantitatively the effect of absorbed rain water on fracture toughness woven sisal fibers ply and E-glass fibers ply reinforced with polyester resin hybrid composite material.

5.2. Recommendation

Even though the ASTM standards used in tests, some discrepancies were observed during the test work. In Mode I loading, branching and deviations of the failure from the mid plane were visible problems. This may lead variations in results and is an ongoing research. To resolve the stability problems in compact tension test it has to be an improvement on the end supports by introducing fixture mechanisms such as grooves.

5.3. Future works

From this point of view, regarding sisal-glass fibers hybrid composite several things can be made and improved in the future in which this study couldn't address. These are:

- ✓ Finding of different sisal extraction processes and treatment process for better sisal fiber surface texture.
- ✓ Performing different sisal fibers and fiber orientations by exposing into different environmental conditions.
- ✓ Characterization of the fibers as a form of fine powder type.
- ✓ Finite element analysis for woven sisal-E-glass fiber hybrid composite materials.
- ✓ Studying chemical properties of woven sisal-glass fibers hybrid composite.

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Appendix A: Mechanical properties of materials

Table 8: Mechanical properties of some synthetic fibers [8, 25]

Fiber	Density (g/cm^3)	Tensile strength (MPa)	Tensile modulus (GPa)	Elongation at break
E-glass	2.54	3450	72	4.5
S-glass	2.49	4300	87	5.3
R-glass	2.52	4400	86	5.1
D-glass	2.56	2500	55	4.5
C-glass	2.56	3300	69	4.8
Carbon (HT)	1.8	5000	250	1.6
Boron	2.6	3500	400	0.8
Aramid/Kevlar 49	1.44	3600	131	2.8

Table 9: Mechanical properties of selected natural fibers *[39]*

Fibers	Mechanical properties					
	Density [g/cm^3]	Elongation at break [%]	Tensile strength [MPa]	Young's modulus [GPa]	Specific Tensile strength [MPa/g.cm^{-3}]	Specific Young's modulus [GPa/g.cm^{-3}]
Sisal	1.33-1.45	2.0-14	468-700	9.4-38	23-441	6-15
Jute	1.3-1.45	1.16-1.5	393-773	13-26.5	286-562	9-19
Flax	1.5	2.7-3.2	345-1100	27.6	230-773	18
Coir	1.15	15-40	131-175	4-6	114-152	3-5

Table 10: Properties of sisal fiber *[30, 31]*

Property	Sisal fiber	Property	Sisal fiber
Density [g/cm^3]	1.33	Elongation at break [%]	4-9
Cellulose [%]	65-78	Specific modulus (appr.)	18
Hemicellulose [%]	10-14	Stiffness (kN mm^{-1})	30-40
Pectin [%]	10	Tensile modulus (GPa)	10-40
Wax [%]	2	Tensile strength (GPa)	540-720
Lignin [%]	10	Young's modulus (GPa)	13
Moisture content [%]	10-22	Elongation at break (%)	2.2-3.3
Maximum elongation (%)	5-10		

Table 11: Comparison of textile structures based on characteristics *[41, 42]*.

Property/characteristics	Woven	Warp-knitted	Weft-knitted	Braided	Non-woven
Stiffness	High	Mid-low	Low	Mid-low	Varies
Flexibility	Low	Mid-high	High	Mid-low	Low
Resilience	Mid-low	Mid-high	High	Mid-high	Low
Impact resistance	Mid	Mid-high	High	Mid-high	Low
Rate of production	Mid	High	High	High	Very-high
Cost of production	Mid	Low	Low	Low	Low

Table 12: Properties of thermoset matrices *[92]*

Thermoset resins	Density (g/cm^3)	Tensile strength (MPa)	Youngs modulus (GPa)	Elongation (%)
Epoxy	1.1-1.4	50-90	3	2-8
Polyester	1.2	50-65	3	2-3
Phenolic	1.2	40-50	3	1-2
Polyimide	1.42	70-150	2.5	8-7
Vinylester	1.15	70-80	3.5	4-6