Addis Ababa University

Addis Ababa Institute of Technology

School of Mechanical and Industrial Engineering

Experimental Investigation on Impact Resistance Behavior of Woven Sisal Fiber Reinforced Polyester Composite

A thesis submitted to the graduate school of Addis Ababa University in partial fulfillment of the requirements for the degree of Master of Science

In Mechanical Engineering (Mechanical Design)

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Declaration

I hereby declare that the thesis report entitled "Experimental investigation on impact resistance behavior of woven sisal fiber reinforced polyester composite" is my own work and the information provided in this thesis report is correct up to my knowledge and it has not been submitted to any university to obtain a degree. I bear the responsibility for correctness of the information contained in this thesis report and comply with the regulations of the university and the accepted standards with respect to originality and quality.

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Abstract

Natural fiber reinforced polymer composites (NFRPC) has been used in many applications. These natural fiber reinforced polymer are capable of absorbing impact energy and dissipating it by different failure modes when they are subjected to low velocity impacts. The impact load on NFRPC materials can create internal damage, which significantly reduces their structural strength, and this phenomenon remains a major concern for structural components. Woven natural fiber reinforced plastic composites have better tensile, flexural, compressive strength because of the interlacing of fiber bundles than the mechanical properties of unidirectional and short randomly oriented NFRPC. However, the characterization of impact behavior with different fiber orientation such as $30^0/-60^0$, $0/90^0$, $30^0/-45^0$ and $45^0/-45^0$ woven sisal fiber reinforced polyester composite was not studied vigorously. Thus, this paper concerns about development and characterization of the impact resistance behavior of woven sisal fiber reinforced polyester composite materials experimentally for semi-structural part (such as automotive interior body panels, automotive back seats and automotive interior door panels) by using Izod impact testing setup. Sisal fibers purchased from local market was extracted using manual decortication and water retting process. The $30^0/60^0$, $30^0/-45^0$, $0^0/90^0$ and $45^0/-45^0$ woven sisal fiber was prepared using nailed wooden frame as a wrap and weft guider. On this guide, the fiber orientation both for wrap and weft was marked and nailed according to the orientations. Then the interlacing of wrap and weft threads was made. The woven sisal fiber was impregnated in order to make woven sisal fiber dimensionally stable. After that using 10:1 polyester/ MEKP mixing ratio and 40% by weight of fiber, the composite was developed using hand layup process. A weight fraction of 40% by weight fiber was used because previous studies has showed that it is best fiber-matrix combination. After the laminate was cured, the specimens were cut according to ASTM standard in Natty Metals manufacturing enterprise. The morphology and cross-sectional elemental detection was carried out using SEM assessment in LDI. Finally, impact tests were carried out using Izod impact testing set up in ASTU. The average impact strength of a 40 wt. % fiber $45^0/-45^0$ WSFRUPC test specimen with consecutive wrap and weft tow spacing 2mm was 342.67 J/m and was greater energy compared to the other orientations. But the average impact strength of a 40wt. % fiber $30^0/60^0$ WSFRUPC of test specimen with consecutive wrap and weft tow spacing 2mm was 241.33J/m and was less energy compared to the other orientations. The SEM micrograph analysis result showed a good fiber matrix adhesion. However, porosity and crack were shown in the wet area.

Key words: woven sisal fiber, unsaturated polyester resin, Izod impact, impact strength, SEM analysis, hand layup, v-notch, alkaline treatment, Orientation

Acknowledgement

No one can accomplish anything without others contribution to his/her success or progress and mine holds true too. It is not only by my hard work that I have reached to this stage. My advisors and examiners comments, during my proposal defense, progress and final presentation helped me a lot. I want to thank all these valuable people for their continuous helpful comments and support. I also want to mention my gratitude to those private and government organizations who helped me while buying necessary material for this research study such as atomic educational materials supply Plc and world fiber glass and water proof engineering. I also want to thank Addis Ababa science and technology university (ASTU) and leather development institute (LDI) for their permit to conduct the experimental analysis according to the schedule set during the proposal stage. I also want to thank Belonias Plc for their great help in measuring mass of each woven sisal fiber using digital weight measuring balance.

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Contents

Nomenclature

ε	-	Inter-yarn fabric porosity
K1	-	fiber orientation factors
K2	-	fiber length factors
M_C	-	moisture content
M_o	-	oven dry mass
M_s	-	modulus of a NFRP composite
T_s	-	Tensile strength of a NFRP composite
M_w	-	wet mass
p1	-	wrap pitch
p2	-	weft pitch,
d1	-	wrap circular diameter,
d2	-	weft circular diameter,
t	-	Fabric thickness and
λ	-	Fabric wavelength
V_f	-	volume fraction of fiber
m_f	-	weight of fiber
ρ_f	-	density of the fiber
m_m	-	weight of the resin matrix
ρ_m	-	the density of the resin matrix
C	-	crimp percentage
C_w	-	wrap crimp in percentage.

List of abbreviations and acronyms

ASTM -American Society for Testing and Materials
ASTU -Addis Ababa Science and Technology University
BPO -benzoyl peroxide
CNT -carbon nanotubes
Epc -end per centimeter,
GSM -gram per square meter
LDI -leather development institute
MEKP -methyl ethyl ketone peroxide
MFA -micro-fibrillary angle
NFRPC-natural fiber reinforced polymer composites
NSFs -natural single fibers
Ocpol 711 -trade code for orthophthalic unsaturated polyester resin
Plc -private limited company
ppc -pick per centimeter,
RTM -resin transfer molding
SEM -scanning electron microscope
VBAHT -Vacuum bagging Assisted Hand Lay-up technique
WSFRUPC -woven sisal fiber reinforced unsaturated polyester composite
UD -unidirectional

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Chapter one

1. Introduction

Natural fiber reinforced polymer composites has been used in industry as semi-structural materials. These semi-structural applications include interior automotive body panels, interior automotive door panels, dash board and back seats [1]. They can also be used for door frames, door shutters, window frame and mirror casing [2]. Besides, many of the woven natural fibers are rising as a viable option to glass fiber reinforced composites in industrial applications like packaging, paper making, and composite materials[3]. The impact load on these semi structural materials can create internal damage, which significantly reduces their structural strength, and this phenomenon remains a major concern for structural components. The sisal fibers offer a good reinforcement compared to other natural fibers, owing to the less extraction cost for retting process. Thus, in addition to selecting semi structural material for suitable application and loading condition, studying the impact resistance behavior of sisal fiber reinforced plastic composite for semi structural engineering application is important for better safety and failure minimizations.

1.1. Background

Composites can be obtained by blending two or more macroscopically dissimilar material and can be used as structural materials in many applications including construction, packaging, decoration, automotive and aircraft industries[4]. Based on matrices, composites materials can be classified as polymer matrix, metallic matrix, and ceramic matrix. They can also be classified into fibrous and non-fibrous composites, based on the type of reinforcement. Recent interest has been grown in fiber reinforced polymer composites than conventional materials because of their unique properties such as high strength to weight ratio, lightweight, low processing temperature, high fracture toughness, and high corrosion resistance[4].

Table 1 shows composition of natural fibers[5]

Type fiber	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Pectin (%)	Wax (%)	Ash (%)	Moisture (%)
Henequen	77.6	4-8	13.1	Not determined	Not determined	Not determined	Not determined
Ramie	68.6	13.1	0.6	1.9	0.3	Not determined	10.0
Sisal	65.8	12.0	9.9	0.8	0.3	4.2	10.0
Jute	64.4	12.0	28.2	11.8	0.5	0.5-2.1	10.0
Flax	64.1	16.7	0.2	1.8	1.5	13.1	10.0
Hemp	55-80.2	12-22.4	2.6-13	0.9-3	0.2	0.5-0.8	6.5
Bamboo	48.2-73.8	125-73.3	10.2-21.4	0.37	Not determined	2.3	11.7

Two types of fibers are used as reinforcement in polymer composites: synthetic and natural. Now a days natural fibers are drawing attention over synthetic fibers (man-made glass and carbon fibers) in structural and semi-structural material developments. This is because of their specific properties such as biodegradability, recyclability, low cost, comparable specific tensile properties, environmental friendly and reduced energy consumption [4]. In addition natural fibers have better crash absorbance, flexibility in usage and good sound insulation properties [5]. Natural fibers can be classified into plant based fiber, animal based fiber and mineral fibers regarding their source. Plant based fibers are preferred reinforcements for structural and semi-structural applications because of their high strength property. The content of composition of cellulose in plant based fibers governs their mechanical properties due to the different cell geometric conditions. Henequen, ramie, and sisal have better tensile, compressive and flexural strength among other plant based natural fibers, and sisal is abundantly available in Ethiopia [1]. In addition, sisal fibers have the lowest embodied energy compared to all other natural fibers which is less than 10% of energy associated with glass fibers and less than 1% of the energy associated with carbon fibers i.e. the lowest environmental impact [6]. The thickness of the secondary wall having the highest content of cellulose determines the mechanical property of sisal fibers [5]. The core of the sisal fiber contains lumen while the middle lamella, on the other hand, is responsible to firmly attach the whole micron-sized fiber onto it, maintaining its physical strength as reinforcement elements. The diameter of sisal fiber ranges from $100 \pm 300 \mu m$ and its length is between 1.0-1.5 m. The micro-fibrillary angle (MFA) is the most important factor that affects the impact resistance of natural fiber. The toughness of natural fiber-reinforced polymer composites increased with the increase to MFA to some extent but a further increase in the MFA decreased the toughness of the composites. The optimum MFA of sisal fiber possesses higher toughness than does that of other natural fibers. The MFA of sisal fiber is 21 degrees, whereas for other natural fibers MFA is either higher or lower (higher MFA: 45 degrees for coir; lower MFA: 12 degrees for banana and 14 degrees for pineapple).

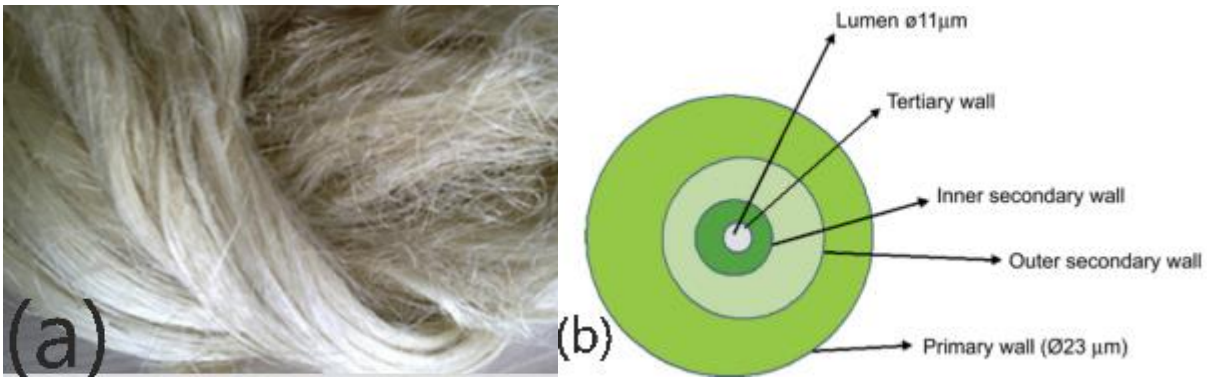

Fig. 1(a) decorticated sisal fiber, (b) micro structure of sisal fiber [7].

Therefore, sisal fiber can be used as reinforcement material for this experimental investigation. Based on the type of bonding present, there are two classes of polymer matrix used for preparing composites: thermoplastics and thermosets. Thermoplastics can be repeatedly softened and re-

formed by application of heat. However, thermosets once undergo a curing process, they cannot be reformed by the application of heat.

Most vegetable fibers used as a reinforcement in composite manufacturing are thermally unstable above 200 ^{0}C[8]. Because of the limitation of this thermal property, those thermoplastics (such as polyethylene, polypropylene, polyvinylchloride, polyolefin etc.) which can be soften below 200 ^{0}c and thermosets (such as unsaturated polyester, epoxy, polyurethane, vinyl ester etc.), which can be cured below 200 ^{0}C are used as a matrix material for natural fiber reinforced polymer composites. Thermoset polymers are used as matrix material in the development of most structural composites because of their low viscosity and simple processing technique such as hand layup, vacuum bagging, and compression molding technique etc. and also, thermosets have high thermal stability, high dimensional stability and stiffness, good resistance to creep, low densities and high electrical and thermal insulating properties[9]. In natural fiber reinforced polymer composites, the function of the matrix is to adhere the fibers together for the efficient transfer of load between them. Unsaturated polyester resin is the most widely used matrix due to its advantages like good adhesion to other materials, high strength, low volatility during cure, low shrink rate, good dimensional stability, low viscosity etc. Because of this relative advantage and its availability in Ethiopia, unsaturated polyester resin is used as a matrix material for the development and experimental investigation on impact resistance behavior of sisal fiber reinforced polymer composite.

1.2. Statement of Problem

Natural fiber reinforced polymer composites has been used in semi structural applications. These semi-structural applications include interior automotive body panels, interior automotive door panels, dash board and back seats. They can also be used for door frames, door shutters, window frame and mirror casing. Sisal fiber is one among the good natural fibers that are used as reinforcement. Even though sisal fiber is abundantly available in Ethiopia, its application is limited to rope use and gypsum reinforcement for roof ceiling application. But we can use sisal fiber for other light use applications. Previous studies has studied the tensile, flexural, and compressive strengths of sisal fiber reinforced polymer composites and showed a good result for semi structural application. However, NFRPC are susceptible to impact loads such as drop of equipment. The impact load on these engineering semi structural materials can create internal damage and results the failure of the structure. The failure could be as a result of delamination, fiber breakage, and shear failure of matrix or fiber pull out. Thus, this work was intended to characterize the impact resistance behavior on woven sisal fiber reinforced unsaturated polyester composite experimentally.

1.3. Objective of the study

1.3.1. General objective

The general objective of this study is to characterize the impact resistance behavior on sisal fiber reinforced polyester composite experimentally.

1.3.2. Specific objective

The specific objectives are:

- ✓ Conducting Izod impact test on $45^0/-45^0$ WSFRPC
- ✓ Conducting Izod impact test on $30^0/-45^0$ WSFRPC
- ✓ Conducting Izod impact test on $30^0/60^0$ WSFRPC
- ✓ Conducting Izod impact test on $0^0/90^0$ WSFRPC
- ✓ Comparing the absorbed energy of $45^0/-45^0$ orientation WSFRPC with other orientations used in this thesis study
- ✓ Comparing the absorbed energy of $45^0/-45^0$ orientation WSFRPC with other orientations used in this thesis study
- ✓ Formulating equations for analytical method of determining absorbed energy
- ✓ Analyzing toughness using ASTM Izod impact testing machine according to the ASTM D256
- ✓ Analyzing absorbed energy using ASTM Izod impact testing machine according to the ASTM D256
- ✓ Determining ISO impact strength.
- ✓ Determining ASTM impact strength.
- ✓ Conducting SEM cross sectional morphology

1.4. Scope of the Study

This paper is intended to characterize the impact resistance behavior on woven sisal fiber reinforced polyester composite material experimentally for semi engineering structure. For the experimental investigation, Izod pendulum impact testing machine fully integrated with computer was used. Generally the scope of this research study is up to accomplishing the specific and general objectives with this pendulum impact testing machine integrated with computer.

1.5. Limitation

There are many challenges that I have faced while conducting this work. Here those challenges are mentioned as a limitation. These limitations are:

- ✓ The Izod impact testing machine used has a precision of two digits after decimal for displaying toughness and absorbed energy using the software installed on the computer integrated to it. But, due to imperfections during manual preparation of woven sisal fiber, hand layup lamination, errors during test specimen cutting and test specimen mounting imperfections, all prepared woven sisal fiber reinforced polyester composite cannot have similar toughness but the result showed that all $30^0/60^0$ and $30^0/45^0$ specimens had

similar toughness value. In addition, all $45^0/45^0$ orientation WSFRPC showed similar toughness value. This might be due to the Izod impact testing machine showed insignificant change of toughness for a small variation of physical or mechanical property of the test specimen. Therefore, the Izod impact testing machine used was not highly sensitive and the limitation of this study.

1.6. Methodology

Throughout this study review of scientific papers was carried out and the gap was identified. Fiber extraction methods was studied. Then the specimen preparation stage was started after treating the decorticated sisal fiber and preparing wooden frame for wrap and weft guides. On this guide, the fiber orientation both for wrap and weft was marked and nailed according to the marks. Then the interlacing of wrap and weft threads was made. Then the woven sisal fiber could be impregnated to prepare prepegs. This prepegs helps the woven sisal fiber to be dimensionally stable. Then using proper resign and hardener mixing ratio and fiber resin mass fraction the composite was laminated using hand layup process. The trapped air could be removed using a roller. When cured, the specimens was cut according to ASTM standard and impact test was carried out. Finally the specimen was investigated using SEM after impact test.

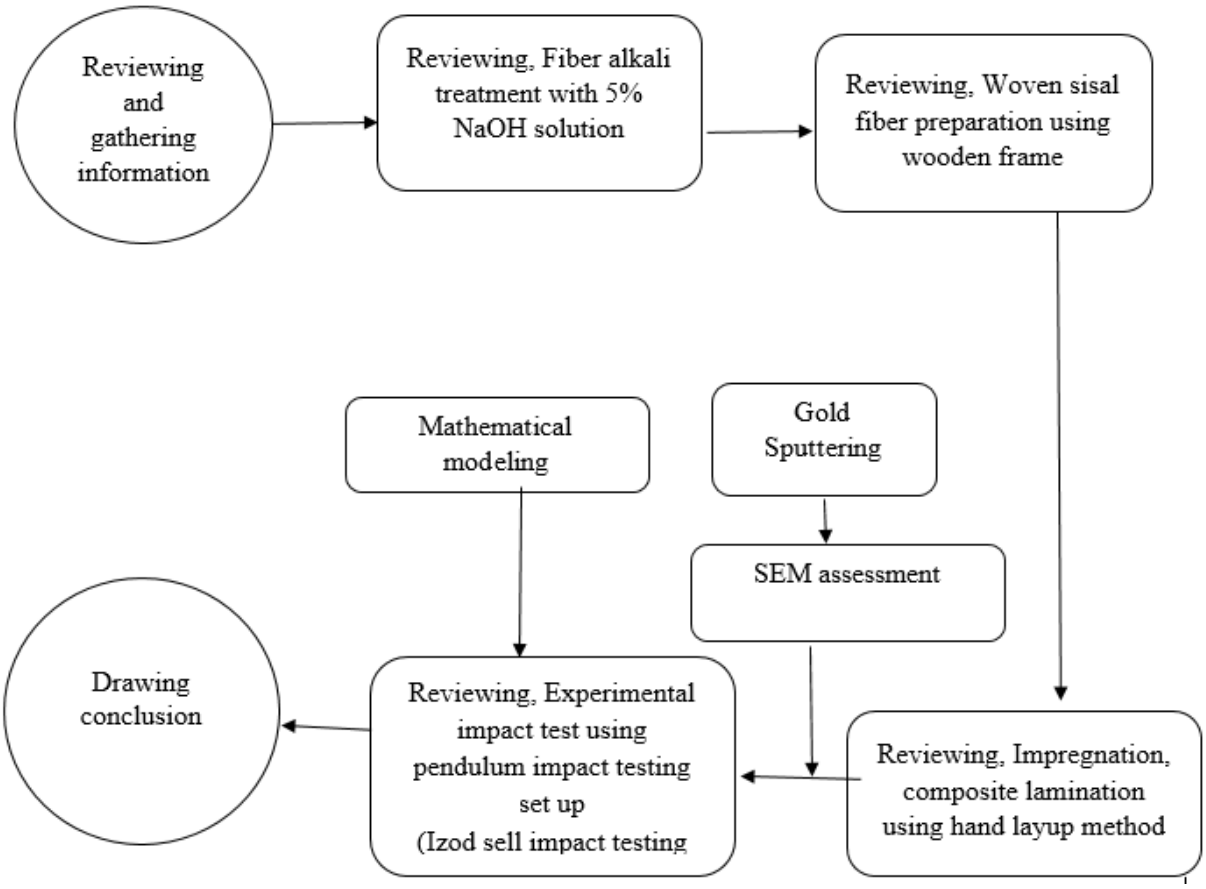

Fig. 2 flow chart showing the method for conducting the research

1.7. Significance

Due to environmental concerns, researchers are drawing their attentions to green composite which are the best alternative to be used in structural and semi-structural applications as compared to synthetic, oil derived, fiber reinforced polymer composites because of their comparable mechanical property. Studying impact properties of natural fiber reinforced polymer composites helps to know the impact strength of the material or the energy required to fracture the material which shows materials ability to resist impact load. Thus, studying the impact resistance behavior of sisal fiber reinforced polyester composite enables to use it for suitable application, as a result failures and accidents can be minimized.

1.8. Thesis Organization

This paper focuses on experimental characterization of impact resistance behavior of sisal fiber reinforced unsaturated polyester composite. The manuscript comprises of five chapters.

Chapter one introduces the back ground of natural fiber reinforced polymer composites, sisal fiber reinforced composites, general and specific objectives, problem statement, scope, limitation and significance of this study work.

Chapter two is about reviewing all relevant research papers regarding natural fiber composite materials and it is organized in the form of their focus area. Therefore papers reviewed about fiber extraction methods discussed first. Then papers about fiber treatment has been discussed. Then papers about fiber form, fiber orientation, fiber volume fraction, composite fabrication method and natural fibers impact property has been discussed.

Chapter three discusses about material conditions and methods used. The materials required for the experimental investigation are discussed. Then according to ASTM D256 impact testing standard, the dimension of the specimen has been described. The methods used, the conditions applied and test rigs used for this experimental investigation is also presented in this chapter.

Chapter four is about data analysis and results. In this chapter, the results of experimental investigation can be briefly described and discussion of the results can be presented. In addition the SEM micrograph result has been discussed.

Chapter five is about Conclusion and recommendation. Conclusions and recommendations can also be drawn from the results. In addition the future work can be described. Finally, references and appendix can be presented.

Chapter Two

2. Literature review

The property of laminated natural fiber reinforced polymer composite depends on the quality and property of fiber, property and quality of polymer, fiber extraction technique, method of fiber treatment and other factors. Different conditions affect the fiber quality. The main conditions are (i) growth of plant (plant species, location of crop local climatic conditions) (ii) harvest phase (age of the fibers, fiber thickness and fiber adhesion), (iii) supply phase (method of transportation, storage time and conditions) [2]. To obtain best fiber and then best composite, all the above conditions should be optimized. In this chapter, all relevant papers reviewed throughout this study has been described. The papers were reviewed section by section. Therefore papers about fiber extraction, fiber treatment, fiber form, fiber orientation, volume fraction, method of composite fabrication and impact property of natural fiber composites has been reviewed.

2.1. Fiber extraction

Fiber extraction method is one of the many factors that affect the performance of natural fiber reinforced composites [8]. To separate fiber bundles from the bast of fiber plant, two techniques usually employed; decortications and retting (biological or chemical). Chemical extraction methods significantly affect the microstructure of sisal fibers. While water retting is the most common and allows to break down large parts from cellular tissues and its adhesive substances that surrounds the fibers, enabling the separation of single fibers from the plant [2]. But water retting technique gives low quality fibers and takes longer reaction time (14-28hrs) [2].Therefore, it is better to use mechanical decortications. Ethiopian species sisal agave plant leaf has been sliced longitudinally and decorticated manually to produce the fibers as there was no automated decortication processes[10], [11].

2.2. Fiber treatment

The other factor that affect the performance of natural fiber reinforced polymer composite is the interfacial bonding between the fiber and the matrix[8]. Hydrophilic or water/moisture absorption property of natural fibers can be a cause for presence of voids and weak bonds between the fiber and the matrix, dimensional instability and thickness swelling of the fiber[12]. To avoid this limitation of natural fibers, fiber treatment is required. Fiber treatment can remove impurities and produce better surface topography. There are different chemical treatments for plant fibers as shown in table 2. NaOH fiber treatment method is the most common. This treatment method can be applied in different practices: (i) constant concentration of NaOH for constant period of time, (ii) using different concentration of NaOH for constant period of time, (iii) keeping constant NaOH concentration for different periods and (iv) using different NaOH concentration for different period of time [2]. Among the treatment methods, alkali treatment can be primarily applied for all types of fibers and it leads to fiber fibrillation which breaks down fiber bundles to smaller fibers as a result the wettability of the fiber by the matrix increases. In

addition better fiber-matrix interface adhesion with increased mechanical properties can be obtained [10, 11].

Table 2 chemical treatments for plant fibers [13].

Name of treatment	Chemical(s) used	Chemical structure	Strength of chemical
Benzoylation treatment	Benzoyl chloride	C7H5ClO	-
Cyclohexane modification	Cyclohexane/ethanol	C6H12/C2H6O	1:1 vol/vol
Alkali treatment	Sodium hydroxide	NaOH	5%, 10%, 15%
Fluorocarbon treatment	Perigurard UFC		50g/L
Silicon treatment	Perisoft MSA		20g/L
Isocyanate treatment	Carbon tetrachloride and dibutyl tin dilaurate	CCl4 and C32H64O4Sn	-
Peroxide treatment	Benzoyl peroxide or dicumyle peroxide	C14H10O4 or C18H22O2	6% solution in acetone
Permanganate treatment	Potassium permanganate	KMnO4	0.005% in acetone

However, when the concentration of NaOH exceeds the optimum value, the property of the fiber degrades. Constant concentration of NaOH solution (10%) for constant period of time (3hrs) was used for the treatment of chopped sisal-epoxy composite [1]. Negawo *et al.*[14] has studied the mechanical properties (tensile and flexural) of alkali treated Enset stem fibers reinforced unsaturated polyester composites (non-woven carded form) using 2.5%, 5% and 7.5% NaOH solution and the results revealed that mechanical properties (tensile and flexural) of Enset fiber reinforced unsaturated polyester has improved as the concentration of NaOH solution increased from 2.5% to 5% but when the concentration further increases to 7% NaOH solution, the mechanical properties(flexural and tensile) become degraded. Sreekumar *et al.*[15]has studied different sisal fiber treatment methods (mercerization or alkali treatment, heating at 100 ^{0}C, permanganate treatment, benzoylation and silanization) to improve the interfacial bonding and has compared with the untreated sisal fiber. The results revealed that the tensile and flexural properties of sisal fiber reinforced polyester (chopped form to 30mm length) has improved compared to untreated sisal fiber reinforced polyester but the impact strength of treated sisal fiber reinforced polyester composite has decreased as result of the treatments. Kim and Netravali[16] has studied the effect of tension during mercerization of sisal fiber on the mechanical properties of sisal fiber reinforced composite (unidirectional form). After mercerization treatment (slacked or under tension), according to this study, the fracture stress and young's modulus has increased while fracture strain and toughness has decreased. The study revealed that alkaline treatment reduced both hemicellulose and lignin contents, resulting in an increase the cellulose content of the fiber. In case of tension-M sisal fibers, the fracture stress and Young's modulus much improved by about 35% and 110% while the fracture strain and

toughness decreased by about 39% and 32%, respectively. Although slack-M fibers showed better strength and stiffness, this improvement may be primarily dependent on the increase in the cellulose content. L, S and Velmurugan[17]has studied the impact strength of untreated and 5% NaOH treated sisal fiber reinforced polyester composite (randomly oriented) and the results revealed that the impact strength of treated sisal fiber was lower than the untreated sisal fiber. Because of the hemicellulose content in natural fibers besides the hydroxyl groups, natural fibers absorb moisture [5] unless treated using treatment methods. Natural fiber reinforced polymer composites are required to be stiff as well as tough enough to with stand the applied load during their semi-structural application. In this experimental investigation alkaline treated sisal fiber was used as a reinforcement since it is obvious that in most researches untreated natural composites have high impact resistance and low stiffness compared to treated natural composites but in most semi-structural applications we need both stiff and tough composite material. Thus, constant concentration of NaOH solution (5%) for constant period of time (2hrs) was used for this experimental investigation.

2.3. Fiber form

The treated fiber can be randomly oriented, chopped, unidirectional or multidirectional with different fiber orientation in the preparation of sisal fiber reinforced polyester composite and this affects it performance. Oriented fiber (weave) reinforced polymer composites showed evidenced impact properties compared to powder and randomly oriented fibers [13, 14]. Woven fiber with different fiber orientations can be a good choice as there is a tightness between wrap and weft direction of weave, which offers advantages in terms of good dimensional stability and high packing density [3]. The use of the plain weave technique can add structural strength to the material because it increases both the strength and the energy absorption capacity [3]. The common weaving architectures are plain, basket, herringbone, inter-ply and intra-ply. Rajesh and Pitchaimani[18] has studied the buckling and free vibration behavior of woven natural fiber composite under axial compression experimentally with different weaving architecture. The results revealed that jute-basket type composite has higher buckling strength compared to jute-herringbone and jute-plain composites because flexural modulus of basket woven composite is higher than jute-plain and jute-herringbone composite because tightness between yarn in wrap and weft direction of basket weave was higher compared to other two weaves.

2.4. Fiber orientation

Vasconcellos, Touchard and Chocinski-arnault[19] has studied the tensile-tensile fatigue behavior of a woven fiber hemp/epoxy composite with $0/90^0$ and $+45^0/-45^0$ fiber orientation. The results reveal that the $+45^0/-45^0$ layup has better fatigue strength than $0/90^0$. Also, Sathish *et al.*[20] has found that the tensile, flexural and impact properties of $+45^0/-45^0$ banana kenaf hybrid epoxy composite was better than $0/90^0$ oriented composite when studying the effect of stacking sequence and fiber orientation mechanical and thermal characteristics of banana kenaf hybrid reinforced epoxy composite. During the fabrication of sisal woven fiber, a specially designed wrap yarn guider can be used so that a fiber or portion of a fiber cannot be misaligned

from the line of orientation during impregnation with a polymer resin. Woven sisal fiber with roientations $+45^0/-45^0$and $+30^0/-45^0$ can be impregnated and when cured it can be used in inter-ply form to get the required sisal fiber reinforced polyester composite fulfilling ASTM D256 requirement [21]. Maslinda *et al.*[22] has used specially designed rectangular wooden frame containing nails that acted as the wrap yarn guider on both of its sides when studying effect of water absorption on the mechanical properties of hybrid interwoven cellulosic-cellulosic fiber reinforced epoxy composites.

2.5. Fiber weight fraction

The other factor that affects the mechanical and impact properties of natural fiber reinforced polymer composite is the volume of fraction. Zegaoui *et al.*[23]has studied the influence of volume fraction by adding treated natural hemp fiber as a reinforcement into cyanate ester/benzoxazine blend matrix composites. The results revealed that the mechanical properties has increased as the volume fraction increased from 5 to 20% by increment of 5%. The dispersed chopped silk fiber between plain weave glass fibers increased the impact property through its elastic deformation and bringing plies together [21] using INSTRON DYNATAP drop weight impact testing setup by varying the percentage by weight of silk fiber from 30 to 60% but when the percentage by weight of silk fiber reached 50%, the impact energy has dropped which may be due to the difficult in wetting up the fiber by epoxy matrix during vacuum bagging process. In addition 40% weight fraction of fiber of chopped sisal fiber reinforced epoxy composite [1] has showed better tensile, compressive, flexural and impact property than 35/65%, 30/70%, 25/75% and 15/85% weight fractions. Therefore in this study 40% by weight of fiber with 60% by weight resin can be used.

2.6. Method of composite fabrication

Some of the conventional natural fiber reinforced polymer composite fabricating methods are hand layup, vacuum infusion, vacuum bag molding, resin transfer molding (RTM), direct extrusion, compression molding, compounding and injection molding. Selecting suitable manufacturing process to transform the composite to the final shape has a direct impact on the performance of the NFRPC. But desired properties, processing characteristics of raw materials, shape and size of final specimen and cost can be a criteria for selecting the processing technique. Compression and injection molding can be used for small and medium size product. However, open molding and autoclave processes can be used for large components while pultrusion can be used for fabricating long and uniform cross-sectioned parts. When volume of fraction increased, injection molding cannot be used as the expansion of the fiber in wet condition could cause a sucking effect. Salman *et al.*[3] has used vacuum infusion processing technique to fabricate woven fiber with $0/90^0$ and $+45/-45^0$ fiber orientation of kenaf fiber reinforced polymer composite in studying the physical, mechanical and morphological properties because the vacuum infusion technique provides a number of improvements over traditional methods such as better fiber-to-resin ratio, less wasted resin, very consistent resin usage, and unlimited setup time. The tensile modulus and flexural strength of short abaca/sisal hybrid fiber reinforced

polyester composite fabricated using the thermoset compression molding process at a volume fraction of 0.40 found to be the highest, which indicates effective stress transfer between the fiber and the matrix [24]. According to this study, Sisal/polyester composites displayed the best damping behavior and highest impact strengths compared to abaca/polyester and hybrid composites. However, maximum stress transfer between the fiber and the matrix was obtained in composites with a volume ratio of banana and sisal equal to 3:1. The tensile strength and flexural modulus reached their maximum at this volume ratio, while the impact strength reached its minimum. In this experimental investigation, because polyester resin has relatively fast curing rate, relatively low viscosity and relatively volatile, hand layup composite lamination technique can be used. The other reason is that there is no other means of composite lamination technique in Ethiopia.

2.7. Impact property

Bisaria et al. [25] has studied the variation of tensile, flexural and impact properties of randomly oriented jute fiber reinforced epoxy composite based on the length of jute fiber used. The results revealed that, using Izod impact test set up, the impact strength and impact energy has increased as the length of jute fiber in randomly oriented jute fiber reinforced epoxy composite has increased from 5 mm to 20mm. A similar study on randomly oriented short sisal fiber reinforced epoxy composite[26] varying the sisal fiber length from 5mm to 20mm keeping the 30%wt constant revealed improved impact property compared to the other length of the fiber. In another study varying volume fraction from 10% to 30% and thickness of specimen 2mm to 6mm of 10 mm length 5%NaOH treated and untreated sisal fiber reinforced unsaturated polyester composite [17] revealed that the impact strength has increased as the thickness of the specimen increased for both treated and untreated 10mm length sisal fiber and untreated fiber has given better impact strength (3.581Nm) than treated sisal fiber (1.962Nm) at 6 mm specimen thickness and 30%wt.

Blended poly(butylene adipate-co-terephthalate) which is 40%wt and poly(butylene succinate) which is 60%wt has been used as a matrix material and miscanthus natural fiber as reinforcement[27] and the blended matrix has better impact resistance property before it is reinforced with miscanthus fiber. It also revealed that when the length of chopped miscanthus fiber reduced from 4mm to 2mm, the bio composite showed improved impact resistance. Due to the difficulty of wetting the fiber during processing, optimum fiber aspect ratio is required for better impact strength result [28] and by varying the fiber aspect ratio of hemp fiber reinforced polycaprolactone composite using Zwick/Rowell HIT230F drop weight impact testing result, hemp fiber with aspect ratio of 26 has better impact resistance result both on dry and wet condition that fibers with aspect ratio of 19, 30 and 38. On ther other had because of effect of the alkali treatement removed hemicellulose, waxes, lignin, and other impurities from the fiber bundles, drop impact resistance has decreased at all energy levels[29] and this due to the load direction of the drop-weight impact test was perpendicular to the fibre bundles. zuan et al.[29] has studied the impact response of Pennisetum purpureum-E-glass hyberdized reinforced epoxy composite under moisture exposure and different temperature exposure (room temperature and

elevated temperature. The result also revealed that as the samples exposed to moisture (as duration of exposure increases), the impact rsistance decreases. As temperature increases, the absorbed energy increases but lower relative to energy absorbed in case of untreated and moisture exposure. Therefore, the fibre treatment did not improve the impact strength of the composites. Short randomly oriented bentgrass reinforced polyester composite showed impact strength of 70.86J/m[30] for 40% by volume of fiber. The fiber was treated with 5% NaOH concentration. In another study, the impact strength of short randomly oriented sisal fiber reinfoced epoxy composite was 65.63J/m[30]. Where as the impact strength of unidirectional 0,90,0 sisal fiber reinforced epoxy composite was 1.35KJ/m^2[30]. The absorbed energy of woven kenaf fiber reinforced polyester composite of $0/90^0$ and $45^0/-45^0$ orientation tested according to ASTM D5229 standard showed about 0.5 and 0.7 percentage of absorbed energy respectively [3]. The impact strength of chopped sisal fiber reinforced polyester composite treated with 5% NaOH solution showed impact strength of about 300J/m which was lower than the impact strength of untreated chopped sisal fiber reinforced polyester composite[15] but in practice we need bboth tough and stiff materials so that treatment is always necessary. Woven kenaf fiber reinforced epoxy composite fabricated by hand layup technique with $0/90^0$ orientation and woven kevlar fiber reinforced epoxy composite fabricated using similar procedure was tested by charpy impact test [31]. In addition woven kenaf and kevlar hybride fiber reinforced epoxy composite was tested and the results were compared. The study of impact properties of hybrid pamyra palm stalk and jute fiber reinforced unsaturated polyester composite [32] fabricated by compression in bi-layer unidirectional form reveals that 100%wt palm fiber reinforced polyester composite (36 KJ/m^2) has improved impact while 100%wt jute fiber has given least impact strength(25KJ/m^2) but the hyberdization effect has reduced impact strength. A. A. Betelie, T. Sinclair, and Y. Li,[1] Has showed better impact strength (about 24.49KJ/m^2) of chopped sisal epoxy composite manufactured using hand layup technique.

Thus the best of the variables used in the previous research studies such as manual decortication and/water retting, 5% NaOH solution fiber treatment and 40% by weight of fiber was used. The gap identified was regarding the fiber form. In the previous studies random orientation, and unidirectional orientation of 0, 90, 60, 45, and 30 was used in different stacking sequence. On natural fibers other than sisal was used in woven form with $0/90^0$, and $45^0/-45^0$ orientations. But sisal fiber in woven form has not been studied vigorously. Thus, in this experimental investigation $30^0/-60^0$, $0/90^0$, $30^0/-45^0$, and $45^0/-45^0$ orientation woven sisal fiber reinforced polyester composite was carried out.

Chapter Three

3. Analytical methods and conditions

In this chapter, materials required for the preparation of sisal fiber reinforced polyester composite, extraction and treatment methods, composite preparation has been discussed. In addition, the fiber orientation, fiber form, volume fraction and fabrication method has been discussed. The dimension of the test specimen and also the test rigs used was also presented.

3.1. Materials

For this experimental investigation, materials such as sisal fiber and pre-accelerated unsaturated polyester resin with methyl ethyl ketone peroxide (MEKP) hardener was utilized in order to manufacture the composite material specimen. Also sodium hydroxide (NaOH) and distilled water was used in order to treat the sisal fiber to reduce water absorptivity property and interfacial adhesion. Pure or distilled water was used to wash the fiber before and after treatment because the impurities in mineral water may react with NaOH. And distilled water avoids this problem.

3.1.1. Sisal fiber

Sisal fiber is one of the most widely used natural fibers and it has obtained from sisal plant. Each leaf contains a number of long, straight fibers which can be removed in a process known as decortications. The quality of the fiber obtained from the sisal plant depends on the geographical location, age of the plant and the extraction method. During decortications, the leaves are beaten to remove the pulp and plant material, leaving the tough fibers behind. The fibers can be spun into thread for twine and textile production, or pulped to make paper products[33]. Sisal fiber has grown in most parts of Ethiopia especially in northern parts of Ethiopia, it is abundantly available. However, sisal fiber has not been industrially process yet but in addition to using as a rope and towing, farmers used to sell sisal fiber to building construction contractors. Building contractors used this sisal fiber for reinforcing gypsum. Local sisal fiber extracted by decortication and water retting was used in this work.

3.1.2. Polyester resin

Polyester resins can be made by a dibasic organic acid and a dihydric alcohol. They can be classified as saturated polyester, such as polyethylene terephthalate, and unsaturated polyester. Ortho-phthalic polyesters are made by phthalic anhydride with either maleic anhydride or fumaric acid. Isophthalic polyesters, however, are made from isophthalic acid or terephthalic acid.

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. Ocpol 711 was supplied in 220 Kg new steel drums with close top. The resin was pre-accelerated and has outstanding water resistance. For this experimental investigation 3 liters of unsaturated polyester resign was purchased from world fiber glass and

water proof engineering. Then keeping the percentage by weight composition of 40% by weight of fiber, appropriate amount of polyester resin was used.

3.1.3. Catalyst/hardener

The most frequently used catalyst is methyl ethyl ketone peroxide (MEKP) or benzoyl peroxide (BPO) and the amount varies from 1-2%. The catalyst will decompose in the presence of the polyester resin to form free radicals, which will attack the unsaturated groups (like C=C) to initiate the polymerization. The processing temperature and the amount of the catalyst can control the rate of polymerization, the higher temperature or the more the catalyst, the faster the reaction. After the resin turned from liquid to brittle solid, post cure at higher temperature may need to be done. The purpose of the post cure is to increase gelation time of the resin by complete cross-linking. The properties of the polyester resin are affected by the type and amount of reactant, catalyst and monomers as well as the curing temperature. The higher the molecular weight of polyester and the more points of unsaturation in molecules, the higher is the strength of the cured resins. Orthophthalic polyesters are environmentally sensitive and have limited mechanical properties. They have been replaced in some applications by isophthalic polyesters due to the excellent environment resistance and improved mechanical properties of the latter. The hardener is MEKP purchased from world fiber glass and water proof engineering located in Addis Ababa and its grade is K10. Hardener/MEKP: High activity MEKP – gives fast gel and cure time for wide variety of ortho and Isophtalic resin systems. To start the curing reaction, take 100 parts of resin. Catalyst K 10 should be added to the resin system shortly before application to initiate the polymerization reaction. It is important to add the catalyst in carefully measured amounts to control the polymerization. Too much catalyst will cause too rapid a gelation time, whereas too little catalyst will result in under cure. The ratio of unsaturated polyester resin to the catalyst is 10:1 according to manufacturer's recommendation. NaOH is purchased from atomic educational materials supply Plc located in Addis Ababa.

3.1.4. Other accessory materials and tools

Materials such as wax and nylon and tools such as brushes and paint rollers was used for preparing specimens for this experimental investigation.

Fig. 3 tools and accessory materials

Wax can be used as a releasing agent during the hand layup process. Whereas tools such as volumetric flasks, brushes and paint rollers can be used for impregnating woven sisal fibers during prepegs preparation and during lamination of composites.

3.2. Dimension

The dimensions of impact test specimens are prepared according to the ASTM D256-10 standard (figure 4). The geometry of the test specimen was also prepared conforming to the standard. This test specimen was clamped on the Izod anvil following ASTM D256 standard procedure. The dimension was measured using a digital caliper. This digital caliper has a precision of two digits after decimal.

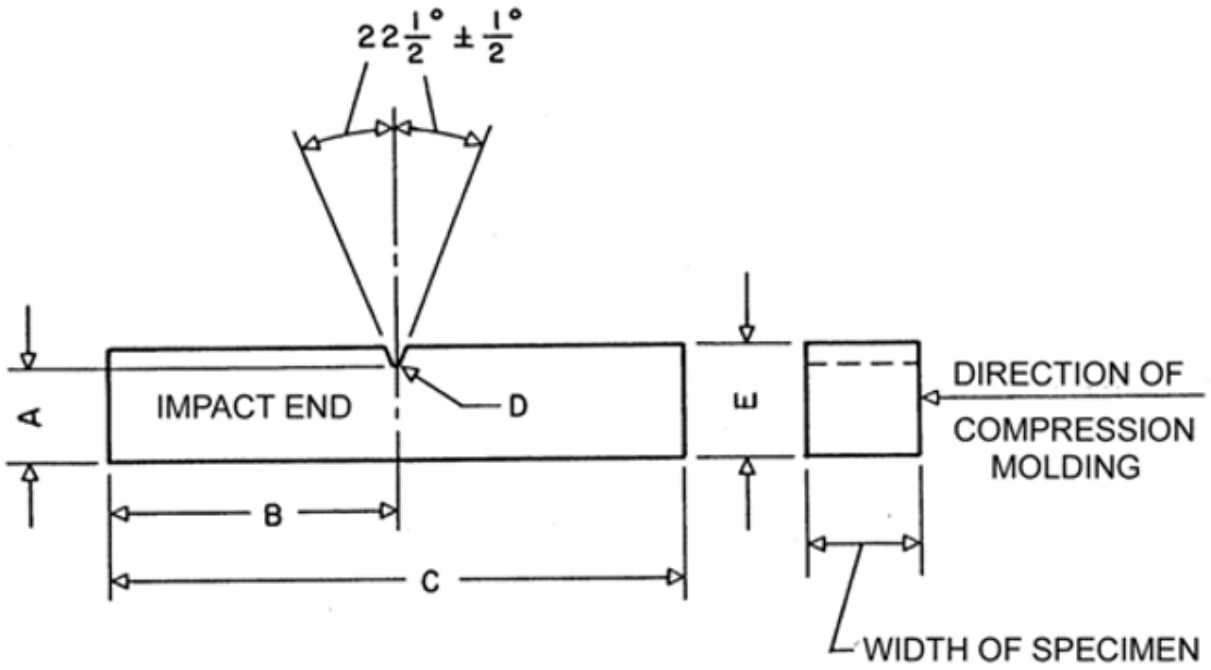

Fig. 4 impact testing specimen dimension (A=10.16±0.05mm, B=31.8±1.0, C=63.5±2.0mm, D=0.25R±0.05, E=12.70±0.20mm, width=3.0mm-12.7mm)[34]

According to this standard, the length of the impact test specimen shall be 63.5±2.0mm and its height 12.70±0.20mm. Whereas molded specimens shall have a width between 3.0mm and 12.7 mm (0.118 and 0.500 in.). All specimens having one dimension less than 12.7 mm (0.500 in.) shall have the notch cut on the shorter side. Otherwise, all compression molded specimens shall be notched on the side parallel to the direction of application of molding pressure. Therefore the specimen was prepared having a length 65mm, height 13 mm, and thickness 3mm and the notch was prepared on the shorter side as shown in figure 5.

The notch in the Izod specimen serves to concentrate the stress, minimize plastic deformation, and direct the fracture to the part of the specimen behind the notch. Scatter in energy-to-break is thus reduced. However, because of differences in the elastic and viscoelastic properties of plastics, response to a given notch varies among materials.

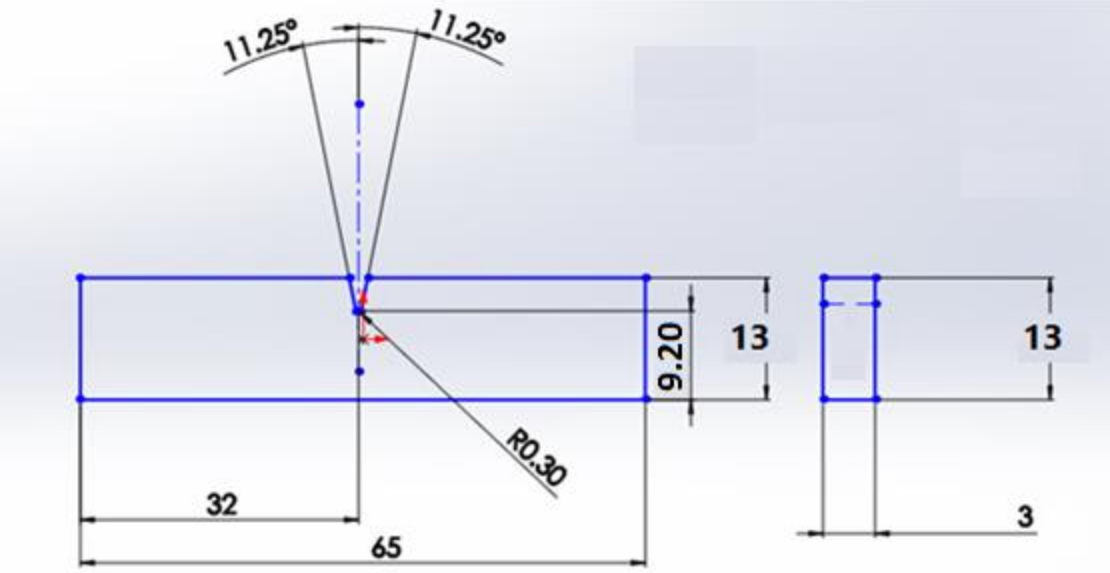

Fig. 5 dimensions of impact test specimen (all dimensions are in mm)

3.3. Methods

The specimen preparation stage was started after treating the decorticated sisal fiber with 5%NaOH solution and preparing wooden frame for wrap and weft guides. On this guide, the fiber orientation both for wrap and weft was marked and nailed according to the orientation angles. Then the interlacing of wrap and weft threads was made. The woven sisal fiber was impregnated to prepare prepegs. The composite was laminated using hand layup process. When cured, the specimens was cut according to ASTM standard and Izod impact test was carried out. In addition the specimen was investigated using SEM for cross sectional morphology.

3.3.1. Extraction of sisal fiber

Sisal fiber has a sword shaped leaf with teeth at the edges. Sisal fiber can be extracted from sisal leaf mainly by retting and decortication process [7]. The mechanical decortication, which uses a machine used to strip fiber bundles from the leaf by crushing and beating using rotating wheel set with blunt knives so that only the fibers remain, and scraping are among the decortication techniques. The water retting and chemical retting processes are employed in extracting fiber from sisal leaves. Retting is the process of subjection of crop or deseeded straw to chemical or biological treatment to make the fiber bundles more easily separable from the woody part of the leaf to facilitate the removal of fiber bundles. Two traditional types of retting; dew and water retting can be used but in Ethiopia water retting process is used because dew retting is heavily dependent on the geographical location, produces coarser and lower quality fibers than those produced using water retting technique. Water retting entails the soaking of stems in water (ponds or tanks and slow moving rivers). Water retting requires large amount of clean water, it can be used to produce relatively large volume of fibers with in specified period of time and it also results in high quality fibers. In retting process the sisal leafs are cut from sisal plant and it

was immersed in water (river, pond or tank) for 15 days until it becomes decay. The retted leafs were washed in running water and then sisal fiber was cleaned. The obtained fiber was dried under sunlight for 2 days. This process takes relatively less time compared to dew retting and it is economical. Ethiopian species sisal fiber used as a reinforcement in this experimental study was purchased from the local market extracted by farmers using manual decortication and water retting process in a pond and then decorticated to separate the fiber from the impurities.

3.3.2. Treatment of Sisal fiber

This process of treatment of natural fibers with alkali is known as mercerization. Mercerization reduces fiber diameter, thereby increasing the aspect ratio, which leads to the development of a rough surface topography that results in better fiber-matrix interface adhesion and an increase in mechanical properties [33]. Natural fibers has a hydrophilic nature while polymers have a hydrophobic nature. Because of this hydrophilic characteristics, natural fibers absorb moisture and this affects their performance in their structural application. The moisture content can be calculated as [31]:

$$MC(\%) = 100\left(\frac{M_w - M_o}{M_o}\right) \quad \text{.....(1)}$$

Where Mo and Mw refer to the oven dry and "wet" masses of fibers respectively.

Unless chemically treated, hydrophilic property of natural fiber results poor compatibility with polymer matrix which they have hydrophobic nature. This results poor fiber surface properties. In order to modify the fiber surface properties, appropriate chemical treatment was used for treating natural fibers. In other words, chemical treatments can be applied to give improved interfacial adhesion characteristics between the fiber and resin matrix, resulting in improved surface wettability of the fiber against the matrix. The main purpose is to remove the 'OH' coating from the natural fiber by means of chemical treatment and to increase fiber surface roughness [2]. Chemical modification of the natural fibers is a process of permanently altering the nature of fiber cell walls by grafting polymers on the surface of fibers. It may happen also with bulking or cross-linking within the fiber cell wall. The chemical modification provides more dimensional stability, reduce water absorption capacity and give resistance to fiber against fungal decay. Alkaline treatment or mercerization is the most commonly used chemical method which removes a certain amount of lignin, wax and oils covering the external surface of the fiber cell wall. It can be used to disrupt the hydrogen bonding in the network structure, thereby increasing the surface roughness. The removal of intra-crystalline and inter-crystalline lignin and other waxy surface substances by the alkali substantially increases the possibility for mechanical interlocking and chemical bonding[35]. NaOH is a good bleaching and/or cleaning agent to remove hemicellulose, lignin, wax and other impurities on the surface of plant fibers as a result better interfacial adhesion can be achieved. Treatment of sisal fiber in a 5% solution of sodium hydroxide resulted in more rigid composites with lower porosity and higher density. The treatment can be used to improve the adhesion characteristics, due to improved work of adhesion because it increases the surface tension and surface roughness. Due to this reason, alkali treatment was used for this experimental investigation. Sisal fiber was washed using distilled

water to remove impurities. Then sisal fiber was dried. Then sisal fiber was soaked in 5% NaOH solution for 2hrs and put into 5% acetic acid solution to neutralize the alkali. In addition, acetic acid is used to remove hemicellulose and other fatty materials from the surface of sisal fiber[2]. Finally sisal fiber was washed with tape water and dried.

The sisal fibers were surface treated according to the following steps

A. The sisal fibers were washed several times with distilled water in order to remove the unwanted attached impurities and dirt.
B. For the alkali surface treatments, appropriate quantities of the NSFs were thoroughly rinsed in the NaOH solution (5 wt%) for 2 hr., then neutralized by washing with acetic acid solution and then by continuously washing several times with distilled water. The distilled water improves the quality of treatment, as there was no reaction with NaOH by active minerals incorporated in it. In addition, weighing sodium hydroxide based on designed concentration; that is a 5% NaOH solution, 100 g NaOH was dissolved in 2 liter distilled water[36].
C. The resulting fibers were room dried at a room temperature for 48 hr. with sun exposure.

Fig. 6(a) washing sisal fiber with 5% NaOH solution, (b) Sealing sisal fiber immersed in 5%NaOH solution (2Hrs)

3.3.3. Fiber form

Various fiber semi products or preforms can be applied to fulfill specific requirements in terms of drape and reinforcement depending on the particular application are: needle felt non-woven or mats (easy to drape, for minor and medium stress levels), woven fibers, non-crimp fibers, and UD fiber semi products (limited draping properties, for highly loaded structures). Unidirectional both single layer and angle layer laminate fiber misalignment error leads to premature shear failure and low tensile strength[37]. In making fiber reinforced polymer composites, woven fiber form is the most common type of reinforcement form due to good dimensional stability, the simplicity in composite layup process and simple strength estimation using classical lamination

theory. According to previous researches, woven fiber form has showed improved mechanical properties than unidirectional and randomly oriented/ chopped fibers. Sisal Woven fiber can be intra-ply and inter-ply arrangement. For a single fiber woven fiber reinforcement, inter-ply form is used. The most common inter-ply form woven fiber are plain weave, basket weave and herringbone weave forms. Among the woven fiber, plain weave has better mechanical properties because it more stable and has optimum inter-yarn fiber porosity and crimp effect whereas basket weave is less stable and herringbone weave form has high crimp effect which also results high porosity in fabricating composite laminates. Inter-yarn fiber porosity is the ratio of the projected geometrical area of the opening across the material to the total area of the material[38]. Porosity depends on the size of wrap pitch, weft pitch, fiber thickness or the size of wrap and weft yarn circular diameter and the fabric wavelength. The wavelength of the weft is defined by the distance over which the wrap pitch wave repeats. The wrap pitch and weft pitch can be used to determine the porosity while the weft wavelength can be used to measure the crimp effects of the structure. Inter-yarn fiber porosity, ε, can be calculated using:

$$\varepsilon = \frac{open\ pore\ area}{total\ area} \Rightarrow \varepsilon = \frac{P_1 - P_2}{(P_1 + d_1)(P_2 + d_2)} \quad \text{.....(2)}$$

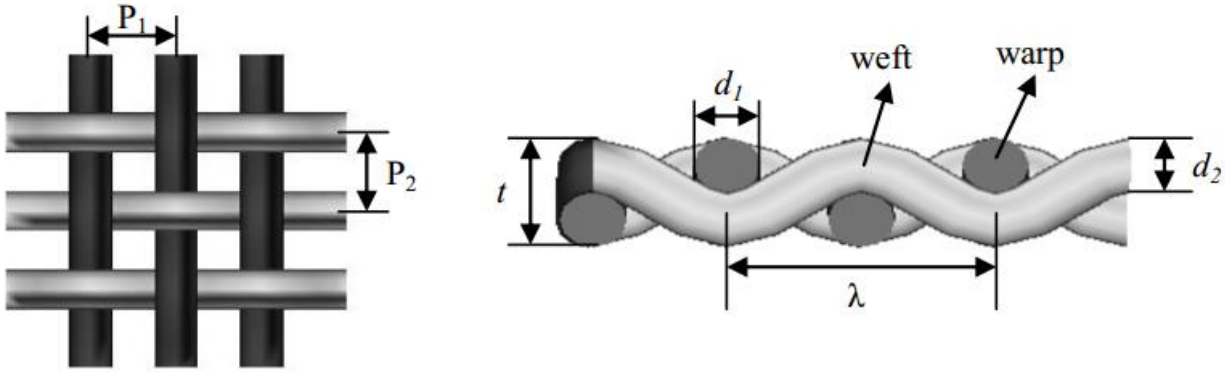

Fig. 7 woven fiber: (a) top view and (b) cross-section view where p_1 is wrap pitch, p_2 is weft pitch, d_1 is wrap circular diameter, d_2 is weft circular diameter, t is fabric thickness and λ is fabric wavelength.

Therefore, single fiber (sisal) plain woven fiber form was used for experimental investigation of impact resistance of sisal fiber reinforced polyester composite.

3.3.4. Fiber orientation

Depending on the orientation of the fibers, the materials behavior of composites can be, for example, quasi-isotropic (all (short) fibers randomly orientated, no privileged direction of mechanical properties), anisotropic (all fibers orientated in one or more directions with corresponding mechanical properties), or orthotropic (fibers orientated in mainly two directions rectangular to each other and showing corresponding materials behavior).

Most natural fibers are used in short randomly oriented form [39] and other fiber orientations need to be investigated to govern mechanical properties of natural fiber. The most common fiber orientations used in the previous studies is $0^0/90^0$ and $45^0/45^0$ and they revealed that $45^0/45^0$[19], [20]has better mechanical properties. Therefore in this study, $30^0/45^0$, $30^0/45^0$, $30^0/45^0$, and $45^0/45^0$ woven sisal fiber orientation was investigated. During processing fiber orientation is influenced by resin flow pattern, viscosity of resin and the mold design [39]. For example injection molding process keeps changing the fiber orientation, and thus cause uneven strength distribution of final NFRP products. Fiber orientation is also influenced by the surface tension and roughness inside the container of the medium, which makes the fiber aligning close toward the wall rather than the center of the barrel [39]. To reduce the influence of composite fabricating process over fiber orientation, fiber pre-impregnation can be carried out using hand layup technique. The fiber orientation has influence on the mechanical properties of natural fiber reinforced polymer composites as much as volume fraction do. For example the modulus and tensile strength of natural fiber reinforced polymer composite can be related with fiber orientation and volume fraction by the following equation [39].

$$M_c = M_f K_1 K_2 + M_m V_m$$
$$T_c = T_f K_1 K_2 V_f + T_m V_m \quad \text{.....(1)}$$

Where K1 and K2 are fiber orientation and fiber length factors, respectively. Mc and Tc are the modulus and tensile strength of a NFRP composite. V is the volume fraction. Subscripts c, f and m denote composite, fiber and matrix, respectively.

3.3.5. Volume fraction

Mechanical properties of sisal fiber has improved as volume fraction increases according to the previous studies and the volume fraction usually varies from 30% and 60% [40]. When volume fraction of natural fibers increased, the impact resistance of natural fiber reinforced polymer composite can be increased but further increase in volume fraction results reduced impact resistance since the wettability of the fiber reduces. For example P Naghipour and others [40] has found that the impact resistance has decreased when 50% volume fraction was used. Therefore 40% by weight sisal fiber reinforced composite with 60% by weight polyester can be produced for this experimental investigation.

3.3.5.1. Density of fiber

The density of Ethiopian species sisal fiber can be obtained by measuring the mass of the fiber used to its volume. The volume of the fiber can be obtained by measuring the diameter of the fiber. The measurement of diameter of sisal fiber is made using digital micrometer. The use of digital micrometer permits measurements with an accuracy of 0.001mm [2]. Then for a specified length of fiber, its volume can be calculated. To get the total volume, total number of fibers used can be multiplied by volume of a single fiber. But this mass density calculation is an approximation technique as the diameter of the fiber may not be uniform or the diameter of different fibers may not have similar value but an average value can be taken.

$$\rho = \frac{m}{v} \quad \text{.....(4)}$$

The mass of the fiber can be measured using beam balance or spring balance.

Fig. 8 mass of 30^0/-45^0 (left) and 45^0/-45^0 (right) woven sisal fiber plies

Then the volume fraction can be calculated as:

$$V_f = \frac{m_f / \rho_f}{m_f / \rho_f + m_m / \rho_m} \quad \text{.....(5)}$$

Where, V_f, m_f and ρ_f account respectively for the volume fraction, weight and the density of the fiber, whereas, m_m and ρ_m represent the weight and the density of the resin matrix, respectively.

In most scientific papers, the density of sisal fiber is described as 1.5g/cm^3 on some papers and 1.33 g/cm^3 on others. But it is clear that the density of sisal fiber varies with geographical location, climate change, sisal fiber species and many other reasons. Because of this it is better to use mass fraction instead of volume fraction. The mass of the single sisal woven fiber ply is 10g and a total of 60g fiber is used. Therefore according to the mass fraction ratio, mass of polyester resin is 120g taking into account that 30% of the polyester resin used can be lost by the brushes or on the mold..

Now using the above mass fraction, the volume of sisal fiber can be determined. Taking the density of sisal fiber as 1.5g/cm^3, 60g sisal fiber has a volume of 40cm^3. Whereas for the polyester resin, from supplies catalogue, the density of unsaturated polyester resin is 1.13g/cm^3. Then 120g unsaturated polyester resin has a volume of 106.194cm^3. From this volume, 31.858cm^3 of resin was to cover the loss of resin during lamination. The remaining volume of polyester resin is 74.336 cm^3 which is 14.336cm^3 greater than the value obtained by the 40/60

ratio. Therefore, in order to avoid mass calculation with wrong estimations, mass fraction is used, that is 40% by weight of fiber is used.

Table 3 variables and number of specimens prepared

Condition of fiber	Fiber orientation	Volume fraction	Number of samples	Total number of samples
Treated fiber	$30^0/60^0$	40%wt	5	5
	$0/90^0$	40%wt	5	5
	$30^0/45^0$	40%wt	5	5
	$45^0/45^0$	40%wt	5	5
Grand total				20

3.3.6. Processing technique

Hand layup/spray layup, compression molding, injection molding, filament winding, resign transfer molding, vacuum infusion, pre-impregnated natural fiber/ polymer tape and vacuum bagging [39] can be used for fabricating natural fiber reinforced composites. Among these methods, compression molding and vacuum bagging techniques are available in Ethiopia but due to the air permeability [35] the compression molding set up cannot be used since it has not vacuum arrangement so that air can get trapped during processing resulting porosity as a defect in the final product. In addition large number of woven plies needs to be prepared in order to produce a specimen according to the ASTM D256 standard. Because according to this standard, the specimen has to be compressed in a direction perpendicular to the notching axis. This requires large number of woven sisal fiber plies and this makes the specimen preparation stage tedious. Since unsaturated polyester resin has relatively fast curing rate, it is difficult to use vacuum bagging. Hand layup process is easily available and simple process to carry out the composite lamination. Due to this hand layup fabricating technique was used. During the hand layup process, trapped air can be removed by using paint rollers. Finally after 5 minutes light compressive load can be applied.

3.3.6.1. Wooden frame preparation

Woven fibers were produced by weaving the fiber yarns using a wooden frame. The wooden frame was manually constructed, and it contained nails that acted as the wrap yarn guider on both of its sides. First, the spacing between consecutive threads can be determined from non-stretched yarn length and number of thread. In addition, thread spacing is also dependent on the gram per centimeter square of the fiber. A 0.0238 gram per centimeter square of sisal fiber was used and 28cm X 15 cm woven sisal fiber ply which has an area of 420 centimeter square was used. A 2 mm diameter nail was used as wrap and weft guider. The gap between consecutive nails was 4mm from center to center. As a result, tread spacing was 2mm between consecutive tows. In a centimeter square of woven sisal fiber six number of wrap threads and six number of weft threads was used. These six number of wefts and six number of wraps weighs 23.8

milligram. In a single sisal fiber thread, nine number of fibers was used and each fiber has an average diameter of 0.1 mm. Therefore a single thread has about 0.9mm diameter or thickness.

Fig. 9 wooden frame for wrap &weft guiding (a) before woven ply preparation (b) after woven ply preparation

3.3.6.2. Woven sisal fiber preparation

Sisal fiber prepegs are prepared with plain weave using $30^0/60^0$, $30^0/45^0$, $0/90^0$ and $45^0/-45^0$ orientation keeping 40% weight fraction.

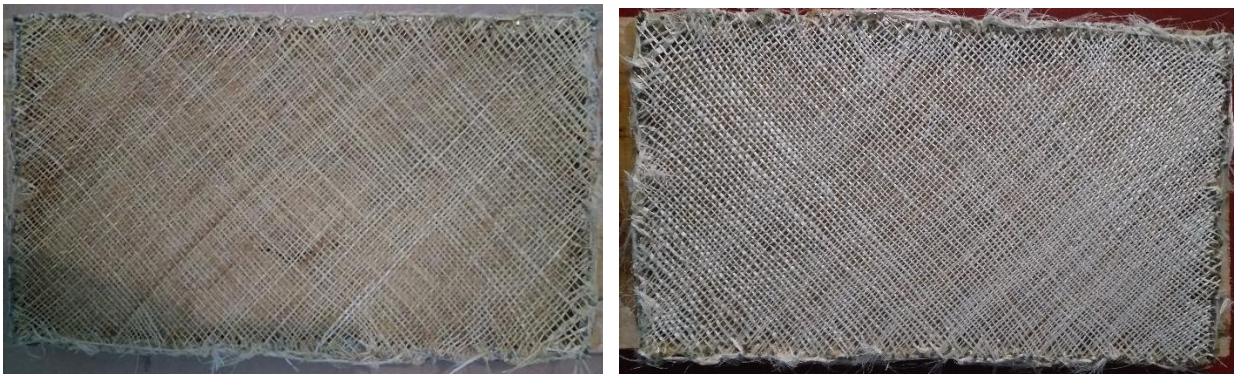

Fig. 10 woven sisal fiber ($45^0/-45^0$ fiber orientation) and ($30^0/-45^0$ fiber orientation)

The weaving process was done by passing the weft yarn over and underneath the wrap yarn, which had been previously arranged on the frame with the help of the wrap yarn guider.

3.3.6.3. Pre-peg preparation

The prepared woven sisal fiber was impregnated by hand layup process. The samples were prepared by respecting some steps. First of all, the mold surface was treated by release anti-adhesive agent to avoid the sticking of polymer to the surface. Wax was used as release anti-adhesive agent. Then, a thin plastic sheet was applied at the top and bottom of the mold plate to get a smooth surface of the product. On these thin plastic sheet (nylon), wax was painted on both bottom and top surface a releasing agent. The layers of woven reinforcement were cut to required

shapes and placed on the surface of the mold. Thus, as previously mentioned, the resin mixed with other ingredients and infused onto the surface of reinforcement already positioned in the mold using a help brush to uniformly spread it.

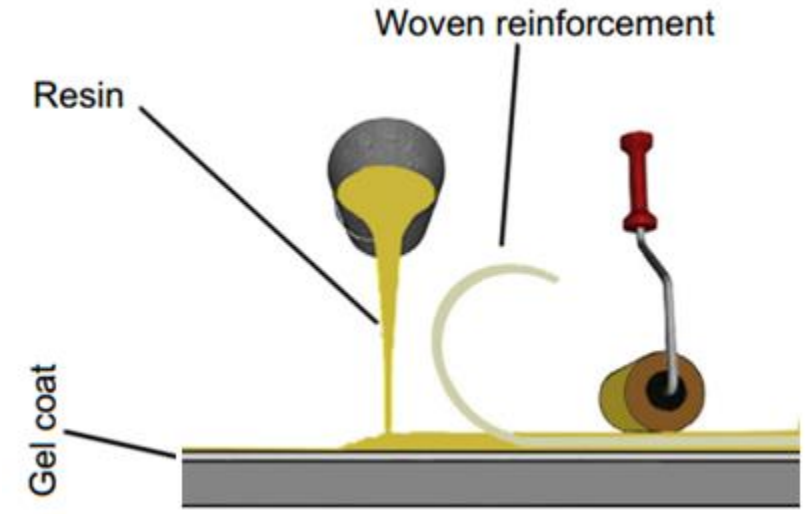

Fig. 11 hand layup process

And then the other mats were placed on the preceding polymer layer and pressured using a roller to remove any trapped air bubbles and the excess of polymer as well. The mold was then closed and pressure was released to obtain a single mat. After curing at room temperature, the mold was opened and the woven composite was removed from the mold surface.

Unsaturated polyester resin of 50ml and 5ml MEKP has been mixed according to the manufacturer's instruction to impregnate each single sisal woven fibers when preparing prepegs. To uniformly distribute the resin over the woven sisal fiber and to remove trapped air, brushes and rollers has been used.

Fig. 12 impregnating woven sisal fiber with unsaturated polyester resin

When impregnated fibers become cured, plies can be cut to the required prepeg size.

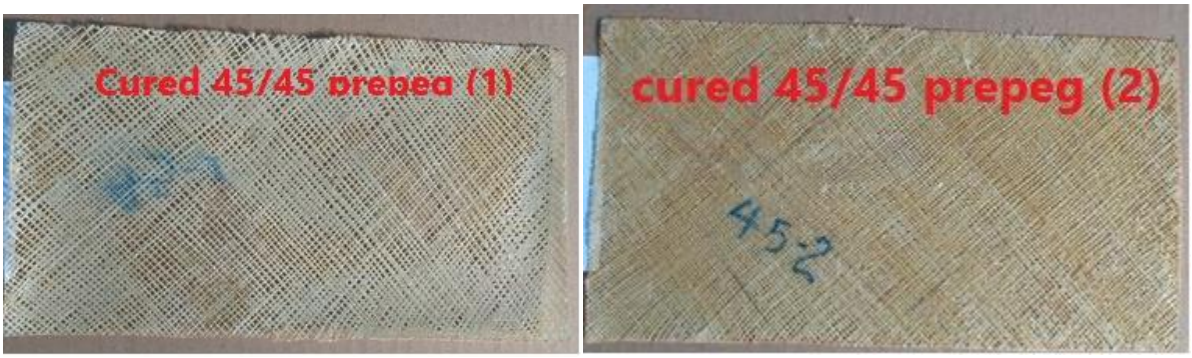

Fig. 13 prepared prepegs (dimension 280 mm x150 mm)

Similarly prepegs for $30^0/60^0$, $0/90^0$, and $30^0/45^0$ plies also cured and cut according to the required size.

3.3.6.4. Composite lamination

Then cured prepegs in inter-ply form was laminated using spray layup process with a dimension of 280 mm x 150 mm x 3 mm to obtain the final test specimen.

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. The formed composite laminates have good properties in mutually orthogonal directions as well as more balanced properties and better impact resistance than the unidirectional 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 (Eq. (9)) 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%.

$$\text{Wrap or Weft crimp\%} = \left\{\frac{(stretched\ yarn\ lenth - non\ stretched\ yarn\ length)}{non\ stretched\ yarn\ length}\right\} x100 \quad \text{.....(9)}$$

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. (10) and mass of fiber can be related by Eq. (11)

Thread spacing, $P = \frac{non\ stretched\ yarn\ length}{no\ of\ thread}$ ……..(10)

$$GSM = \frac{ppc(1+C)xYarn\ count}{1000} + \frac{epc(1+c_w)\times Yarn\ count}{1000} \quad \text{……(11)}$$

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

Unsaturated polyester resin has fast curing rate. Because of that it is difficult to use vacuum bagging process in composite lamination process. Compression molding can be used in the composite lamination. But according to the ASTM standard D256, the direction of compressive load shall be in an axis perpendicular to the notching axis. To do so large number of plies, or 1mm thickness pre-pegs, can be required and stacked in such a way that the thickness of the stacked pre-pegs when compressed should be greater that 65mm which is the length of test specimen. But the woven fiber preparation stage is tedious and time consuming and because of this hand layup process can be used. During the hand layup process, nylon was lain on a smooth table and was painted wax uniformly so that it can be easy to release the laminated composite. Then the stirred polyester resin and hardener was added over the wax.

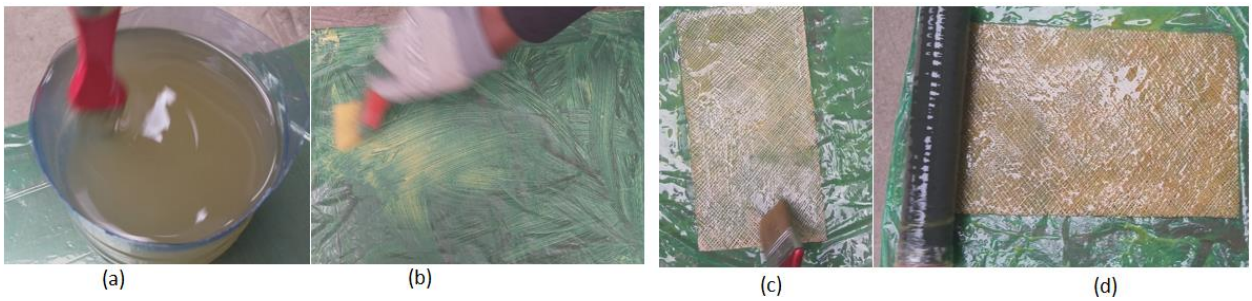

Fig. 14(a) stirring polyester resin and hardener for 5 min, (b) adding wax, (c) hand layup process: adding resin mixture, (d) roving rolling to remove air (right)

Then each pre-peg was added step by step and laminated by adding resin and hardener mixture sequentially and rolled in order to remove trapped air using paint roller.

The manufactured sisal fiber reinforced polyester composites were prepared according to the following steps;

1. Appropriate proportions of unsaturated polyester resin/ MEKP (10:1 based on manufacturer's recommendation and according to previous studies[41] were carefully mixed in a glass beaker and stirred manually for degassing for 5 minutes in order to remove air bubbles.
2. A woven fiber prepared on wooden frame was impregnated using hand layup process.
3. When impregnated sisal fiber reinforced polyester composite was cured at room temperature, finally the specimen is cut into 280mm x 150 mm x 3 mm.

4. Pre-impregnated sisal fiber reinforced polyester composites with dimension 280 mm x 150 mm x 1 mm were laminated using hand layup technique. After that, wax painted nylon was lain over the laminated composite for easy release and light load can be applied over it. Then a 280 mm X 150 mm x 3 mm composite laminate was obtained.
5. Laminated specimens were cured at room temperature.

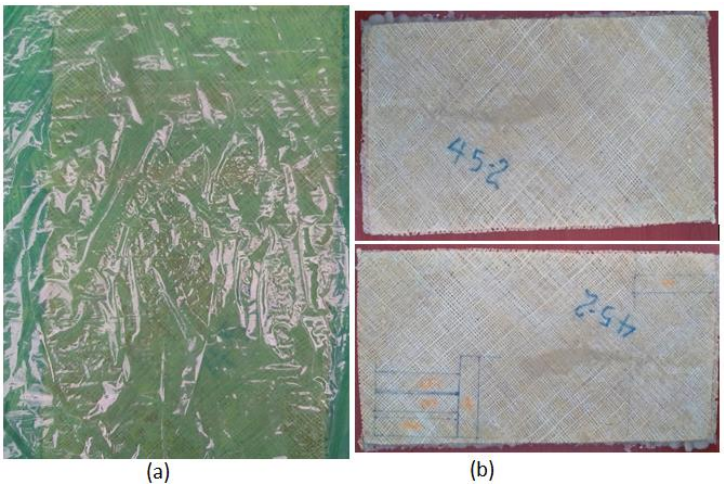

Fig. 15(a) composite lamination left to be cured, (b) cured $45^0/45^0$ specimen and marked specimen size before cut

6. Then the specimens were cut using a machine according to ASTM standard D-256.

Finally, cured composite laminate can be removed from the mold and specimens can be measured and cut on it in order to get the required specimen size according to ASTM D256 standard.

3.3.6.5. Cutting and notching of specimen

From composite laminated samples, the specimen can be cut using jig saw. The specimen can be cut according to ASTM D256 having a dimension of length 65 mm, width 13 mm and depth 3 mm.

Fig. 16 Test specimens cut and notched according to ASTM D256

Notching can be done on a milling machine, engine lathe, or other suitable machine tool. Both the feed speed and the cutter speed can be constant throughout the notching operation. A single tooth cutter shall be used for notching the specimen, unless notches of an equivalent quality can be produced with a multi-tooth cutter. Single-tooth cutters are preferred because of the ease of grinding the cutter to the specimen contour and because of the smoother cut on the specimen. The cutting edge shall be carefully ground and honed to ensure sharpness and freedom from nicks and burrs. Tools with no rake and a work relief angle of 15 to 20° have been found satisfactory.

Specimens may be notched separately or in a group. However, in either case an un-notched backup or "dummy bar" shall be placed behind the last specimen in the sample holder to prevent distortion and chipping by the cutter as it exits from the last test specimen. The profile of the cutting tooth or teeth shall be such as to produce a notch of the contour and depth in the test specimen.

3.3.7. Sputtering

Sputtering is the ejection of atoms by the bombardment of a solid or liquid target by energetic particles, mostly ions. When a surface is bombarded with high velocity positive ions, it is possible to cause ejection of the surface atoms. This process of ejecting atoms from the surface by bombardment of positive ions (usually inert gas ions), by momentum transfer process between the sputter gas and target atoms is commonly known as sputtering (cathode sputtering). Argon is commonly used as the sputtering gas. The ejected atoms can be made to condense on a substrate at an optimal distance from the target to form a film. Apart from the neutral atoms, charged atoms and electrons are also emitted from the surface. The sputtering yield 'S' (number of atoms ejected from the target surface per incident ion) depends on the target material composition, binding energy, characteristics of the incident ion and the experimental geometry. It also depends on the voltage and current (sputter power) at which sputtering takes place.

3.4. Conditions

3.4.1. Impact load

The Izod Impact Test which was named after the English engineer Edwin Gilbert Izod who described it in the 1903 address to the British Association is an ASTM standard method of determining impact strength using a specimen with a V-notch specimen. The specimen is gripped at one end only that allows the cantilevered end to be struck by the pendulum. These methods allows that several notches can be made in a single specimen and the ends broken off one at a time. The load applied on the impact test specimen was impact load at low impacting velocity with cantilever beam arrangement using Izod impact testing machine set up. The maximum impacting load used for this experimental investigation was 90 Joule.

3.4.2. Impact speed

There are a few categories of impact loading, and specifically these are: low velocity (large mass), intermediate velocity, high/ballistic velocity (small mass), and hyper velocity impact. Low velocity impacts occur at a velocity below 10 m/s, intermediate impacts occur between 10

m/s and 50 m/s, high velocity (ballistic) impacts have a range of velocity from 50 m/s to 1000 m/s, and hyper velocity impacts have the range of 2000 m/s to 5000 m/s. In this experimental investigation low velocity impact test was carried out. The velocity range of Izod impact testing machine was calibrated from 2.6 m/s to 5.5 m/s

3.5. Test rig

3.5.1. Mass measuring device

The mass of each woven sisal fiber was measured using digital weight measuring balance. This machine has a capacity of measuring weights up to 40 kg with the precision of three digits after decimal. The device uses LED displays.

3.5.2. Specimen cutting and notching machine

The jig saw can be used for cutting specimens from composite laminated samples according to ASTM D256 impact testing standard dimension. This jig saw can be used in wood processing small scale industries and manufacturing colleges. From 280 x 150 mm2 composite laminate a 65 mm x 13 mm x 3mm specimen was cut in Natty metals manufacturing enterprise. Notching can be done on a milling machine. The notching process can be done using a single cutting tool installed on milling arbor and a single specimen can be notched or multiple specimens can be notched at once. Notching can be done having notch radius 0.30mm and notching angle 22.5^0 according to ASTM D256 standard.

3.5.3. SEM

The JSM-IT300LV scanning electron microscope (SEM) shown in figure 26 (b) in LDI imported from JEOL GmbH (Germany) features an expanded pressure range, large specimen chamber and improved resolution for imaging and characterizing a variety of sample types and sizes. The SEM extends vacuum pressure range to 10 to 650 pA; in low-vacuum mode, this enhances imaging capability for samples that are wet or oily, that outgas excessively or that are nonconductive without pretreatment.

Fig. 17 SEM model: JSM-IT300LV Scanning electron microscope set up (LDI) laboratory

The device features multiple ports for analytical attachments such as energy-dispersive x-ray spectrometers, electron backscatter diffraction, cathodoluminescence detectors, wavelength-dispersive x-ray spectrometers, chamberscopes and heating/cooling sub-stages.

The vacuum chamber accommodates samples up to 300 mm in diameter and 80 mm in height. Sample navigation control, an embedded CCD camera and five-axis stage control allow accurate imaging and analyzing of samples at a wide range of angles and orientations.

3.5.4. Izod impact testing set up

Using Izod pendulum impact testing machine in Addis Ababa science and technology institute /AASTU/ impact resistance behavior can be characterized. This impact testing machine, brand name TE, model JWT-406 operates with pneumatic hammer release and console.

Fig.18 computer integrated Izod impact testing machine model JWT 406

The specimen size and clamping procedure can be accomplished according to ASTM D256 Izod pendulum impact testing standard for plastic composites. The machines with their pendulum-type hammers have been standardized in that they must comply with certain requirements, including a fixed height of hammer fall that results in a substantially fixed velocity of the hammer at the moment of impact. The specimens are standardized in that they are required to have one fixed length, one fixed depth, and one particular design of milled notch. The notch in the Izod specimen serves to concentrate the stress, minimize plastic deformation, and direct the fracture to the part of the specimen behind the notch. Scatter in energy-to-break is thus reduced.

However, because of differences in the elastic and viscoelastic properties of plastics, response to a given notch varies among materials. The following testing parameters may affect test results significantly: Method of fabrication, including but not limited to processing technology, molding conditions, mold design, and thermal treatments; Method of notching; Speed of notching tool; Design of notching apparatus; Quality of the notch; Time between notching and test; Test specimen thickness, Test specimen width under notch, and Environmental conditioning. The Izod impact testing machine with model JWT-406 used for this experimental investigation has the following specification. The power requirement was 3 phase, 220v, 50Hz, 1.5KW and RS 232 data output was used for connection to PC and data acquisition software. The maximum impact energy was 406J and the available impact weight was 90J. The impacting speed range was from 0.3-5.45 m/s and the test was carried out at 5.25m/s.

This Izod impact testing machine in its feature has a safety lock in its raised position. The release of the pendulum from its raised position is vibration free. Sample mounting can be easily accomplished by using pliers or by automatic sample centering system. Electric break can be used to stop the pendulum on its highest position on the return swing for most productive testing. Motorized pendulum can be returned to its latched starting position automatically. The fixing screw is used for advancing and retracting Izod anvil in order to attach the impact specimen firmly (see figure 19 (a)). Also, as shown in figure19 (b)), a quick sample attaching knit can be used for fast specimen attaching and detaching.

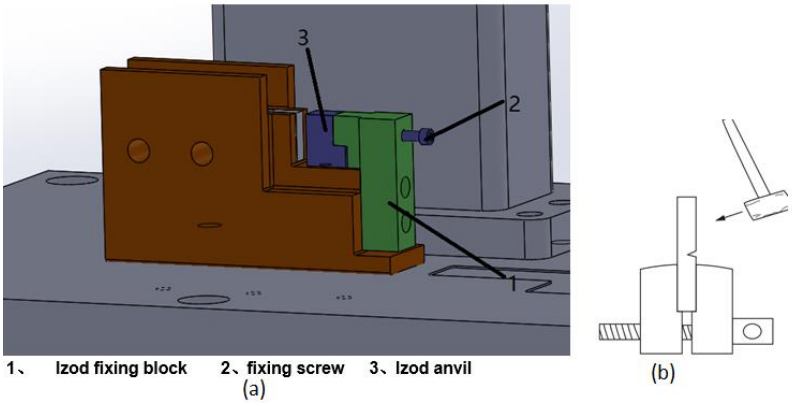

Fig. 19(a) major parts of Izod impact testing anvil, (b) schematic of Izod impact testing

The specimen can be mounted in such a way that the hammer hits on the notch side as shown in the figure 19(b).

Chapter four

4. Data analysis and Results

In this chapter results was presented and discussed briefly. Bar graphs can be used for result data presentation of 40% by weight of $30^0/60^0$, $30^0/45^0$, $0^0/90^0$ and $45^0/45^0$ orientation sisal fiber reinforced polyester composite. In addition to the Izod impact test result presentation was included.

A total of 20 specimens, 5 specimen of each type, tested using Izod impact testing setup integrated to a computer. The computer integrated to the Izod impact testing set up was used to display the potential energy, absorbed energy, compensated energy and toughness. The impact strength of woven sisal fiber reinforced polyester composite was obtained using the absorbed energy and thickness or notch cross sectional area of the test specimen. The absorbed energy of the test specimen was directly recorded on the computer integrated to the Izod impact testing machine. Using this value and the notch cross-sectional area of the test specimen, impact strength was obtained by dividing absorbed energy to the cross-sectional area.

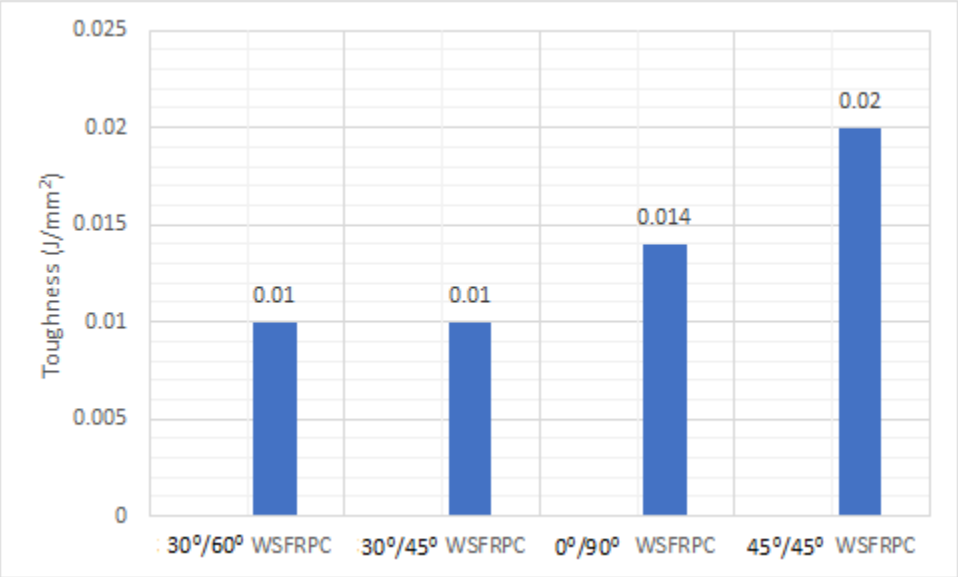

Fig. 20 Average toughness energy of WSFRPC

The absorbed energy of most of the test specimens were different but the absorbed energy of some of the test specimens were similar. All $30^0/60^0$ WSFRPC test specimens showed 0.01 J/mm^2 toughness energy. This could be because the Izod impact testing machine is less sensitive for a small change of absorbed energy. Similarly, all $30^0/45^0$ WSFRPC test specimens showed 0.01 J/mm^2 toughness energy but slight difference of absorbed energy. Even though the toughness of $30^0/60^0$ and $30^0/45^0$ WSFRPC test specimen was similar, $30^0/45^0$ WSFRPC test specimens showed greater absorbed energy. Some of the $0^0/90^0$ WSFRPC test specimens showed 0.02J/mm^2 toughness energy and this test specimens showed greater absorbed energy. All the $45^0/45^0$ WSFRPC test specimens showed 0.02J/mm^2 toughness energy and superior absorbed

energy compared to the other orientation type test specimens. The sample standard deviation for $30^0/60^0$, $30^0/45^0$ and $45^0/45^0$ WSFRPC was zero. This is because there is no variance in the toughness energy of these test specimens which may be as a result the Izod impact testing machine is insensitive to insignificant change in absorbed energy. But $0^0/90^0$ WSFRPC has a standard deviation of 0.0055 J/mm^2 toughness energy. This variance might be from inaccuracies during specimen cutting, specimen mounting on the Izod anvil or non-uniformity in the material composition of the test specimen.

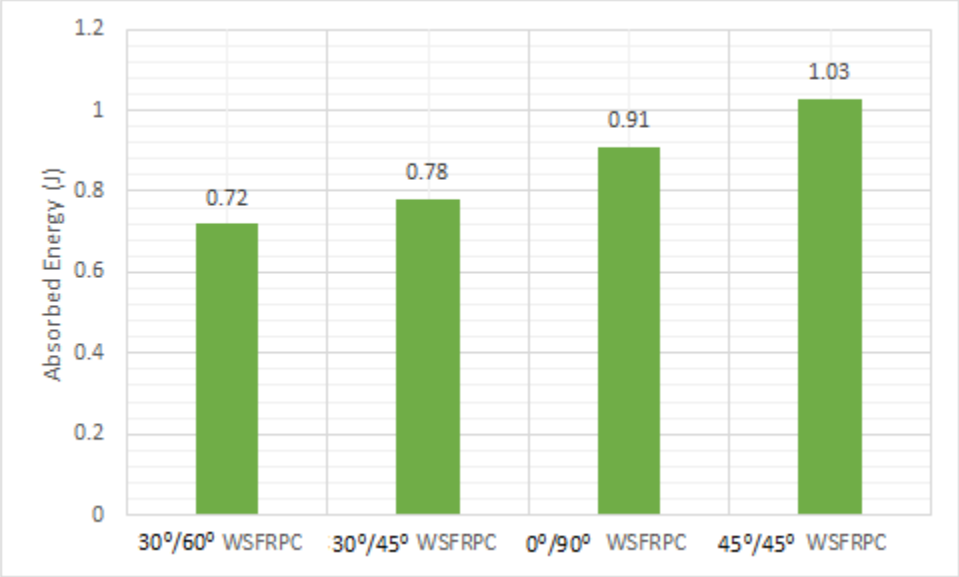

Fig. 21 Average absorbed energy of WSFRPC

The smallest absorbed energy absorbed was 0.64 J for $30^0/60^0$ WSFRPC test specimen and the maximum absorbed energy recorded was 1.07J for $45^0/45^0$ WSFRPC test specimen. All of $45^0/45^0$ WSFRPC test specimens showed greater absorbed energy. The absorbed energy sample standard deviation of $30^0/60^0$ WSFRPC test specimen was 0.061J. Whereas the absorbed energy standard deviation for $30^0/45^0$ and $45^0/45^0$ WSFRPC test specimens was 0.034J. But the absorbed energy standard deviation for $0^0/90^0$ WSFRPC test specimen was 0.09J. Similarly, the ASTM impact strength standard deviation for $30^0/45^0$ and $45^0/45^0$ WSFRPC test specimens was 11.22J/m and 11.4J/m respectively. But the ASTM impact strength standard deviation for $30^0/60^0$ WSFRPC test specimens was 20.61 J/m while the ASTM impact strength standard deviation for $0^0/90^0$ WSFRPC test specimens was 20.61 J/m. This result showed that there is more accuracy and precision in $30^0/45^0$ and $45^0/45^0$ WSFRPC test specimens. But the slight variance among the samples both for absorbed energy and ASTM impact strength may come from the variation in the physical properties of the test specimens such as slight difference in dimension, slight variation in the uniformity of chemical composition of the composite, or variation in speed of cutting the test specimen. The variation may also result from inaccuracy and less precise specimen mounting procedure on the Izod impact testing machine anvil. When we compare the standard deviation of absorbed energy and ASTM impact strength of $30^0/45^0$ and

$45^0/45^0$ WSFRPC test specimens, they has almost similar variance respectively. Thus, there is more precision and accuracy in these test specimens.

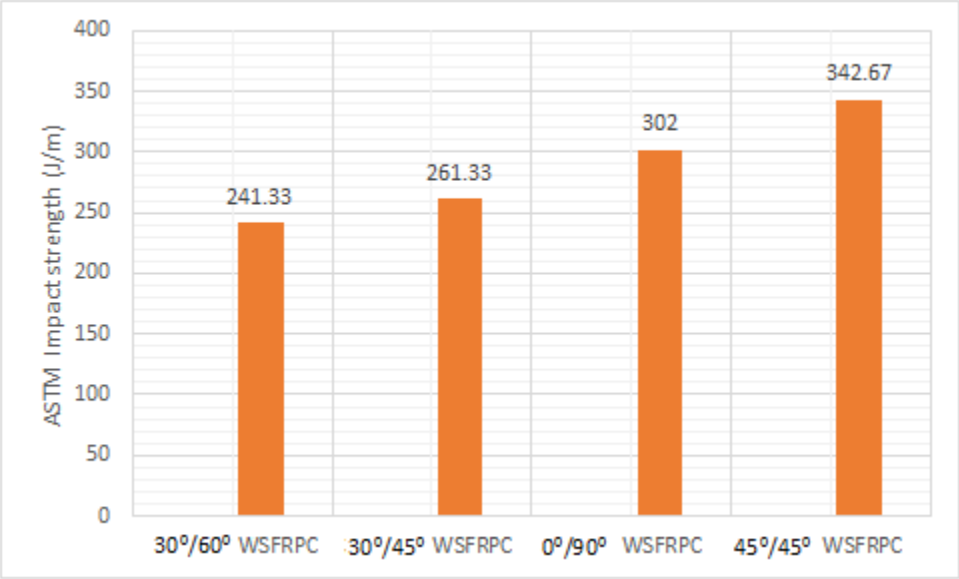

Fig. 22 Average ASTM impact strength of WSFRPC

Compared to the chopped sisal epoxy composite [1] fabricated by hand layup processing technique, the test specimens in this experimental investigation showed greater absorbed energy. The ASTM impact strength depends on the thickness of the test specimen. It was obtained by dividing absorbed energy to the thickness of the test specimen. For similar test specimen thickness, $45^0/45^0$ WSFRPC showed greater ASTM impact strength.

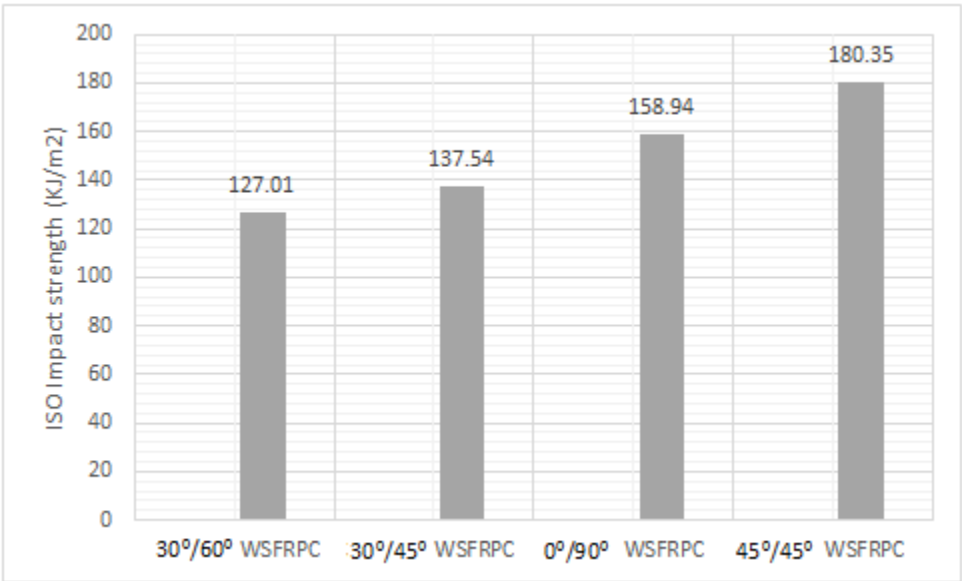

Fig. 23 Average ISO impact strength of WSFRPC

A 45^0/-45^0 WSFRUPC test specimen showed high precision result since individual absorbed energy and impact strength has minimum deviation from the average value compared to the other test specimens. The average absorbed energy and impact strength for 45^0/-45^0 WSFRUPC test specimens were 1.03J and 180.35KJ/mm^2, respectively.

4.1. Discussion and interpretation

The energy absorbed during impact test can be a measure of toughness. The impact strength of the specimen tested was determined from the absorbed energy. ASTM impact strength of WSFRUPC was obtained by dividing the absorbed energy by the thickness of test specimen. Similarly, ISO impact strength was obtained by dividing the absorbed energy by the cross sectional (notch) area of the test specimen.

4.1.1. Mathematical modeling

The impact strength of the woven fiber composites mainly influenced by many factors including matrix intrinsic properties, optimum fiber–matrix interaction, fiber concentration, fiber geometry, fiber–matrix stress transfer efficiency, fiber orientation, and fiber dispersion and distribution. At the same time, the fiber bridging, fiber pull-outs, crack propagation and matrix deformation mechanisms contribute a vital role in the impact rupture of natural fiber reinforced composites.

The predicted impact strength of the composites [26] is ‘‘Y” and it can be represented by Eq. (5) as a function of independent factors

$$Y = f(A, B, C, D) \quad \text{.....(5)}$$

Where A, B, C and D are impact strength influencing parameters.

Keeping all these in mind, the ASTM impact strength can be obtained as:

$$I = E/t$$

Where I is ASTM impact strength, E is the absorbed energy and t is the thickness of the test specimen.

Similarly ISO impact strength can be obtained as;

$$i = E/a$$

Where i is ISO impact strength and “a” is notch area.

The energy absorbed by the impact test specimen was directly recorded on a computer integrated to the test set up using impact test software. In addition the absorbed energy by the test specimen can be calculated analytically using conservation of energy principle. Ignoring energy due to friction, the impactor knife has both kinetic energy and potential energy. Impactor knife has maximum potential energy and falling angle, constant total energy, at its initial falling position. As the impactor knife leaves its initial falling position with some predefined velocity, 0.3 m/sec according to manufacturer’s initial set up, it loses its potential energy and attains its kinetic energy. At the instant of impacting the test specimen, the impactor knife has maximum kinetic

energy and maximum impacting force. Due to the energy absorbed by the test material, the impacting force and kinetic energy of impactor knife decreases and the potential energy increases. When impactor knife attains its maximum rise position, automatic brake can be applied to prevent back swing of the impactor knife. Then the absorbed energy, E, of the test specimen can be calculated analytically as;

$$E = PE_{initial} - PE_{final}$$

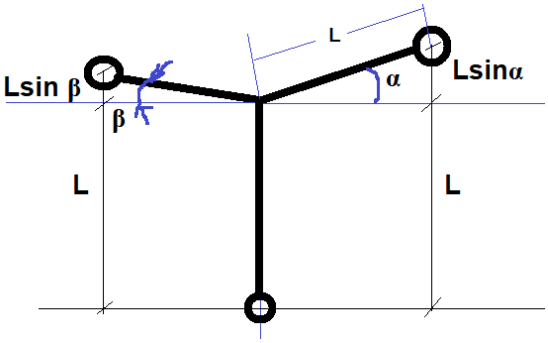

Fig. 24 position of impactor knife before and after impact

$$E = \text{mgL}\,(\sin\alpha - \sin\beta)$$

Where, α--The up angle of the pendulum before the impact

β--The rising angle of the pendulum after the breaking of the sample

The impacting force F(t) during the impact load depend on the impactor kinetic energy or mass m and velocity ν. Initial impactor speed ν0 depends on the free fall acceleration g and downfall height ΔL:

$$v0 = \sqrt{2g\Delta L}$$

Impactor speed ν and displacement s as the time functions are determined by integrating the impact force:

$$V_f(\text{t}) = \text{vo} - (\frac{1}{m})\int_0^t F(t)dt$$

$$\text{s(t)} = \int_0^t (\text{vo} - (\frac{1}{m})\int_0^t F(t)dt)dt$$

The energy absorbed can also be calculated analytically from the change in kinetic energy. Therefore it can be the difference between the kinetic energy at the instant the impactor knife touches the test specimen and the kinetic energy at the instant the impactor knife leaves the specimen after breaking it. After the impact with the specimen the impactor speed gradually decreases as the specimen absorbs the kinetic energy during the impact. The specimen absorbing the impact kinetic energy or the impact energy of the impactor E_{imp} is equal to:

$$E_{imp} = \frac{1}{2}mv^2 = \frac{1}{2}mV_o{}^2 - \frac{1}{2}mV_f{}^2$$

The absorbed energy Eab as the time function is:

$$E_{ab} = \frac{mv_0^2}{2} - \frac{1}{2}m(\text{vo} - (\frac{1}{m})\int_0^t F(t)dt)^2$$

But the kinetic energies are difficult to measure. In addition, the value of resistance to damage was rather difficult to measure due to the factors, such as mounting limit conditions, load magnitude, material strength and stiffness, and the sequence of the specimen layer arrangement. Parameters are estimated with standardized method of impact experiment ignoring the influence of the impact form and the bracket limit conditions.

4.1.2. Interpretation of results

On all $30^0/60^0$, 30^0/-45^0, $0^0/90^0$ and 45^0/-45^0 orientation test specimens, either the test specimen completely broken and divided into two pieces or the fiber bundles hold the two pieces together.

Fig. 25 breakage of the test specimen which the fiber bundle holds the two pieces together

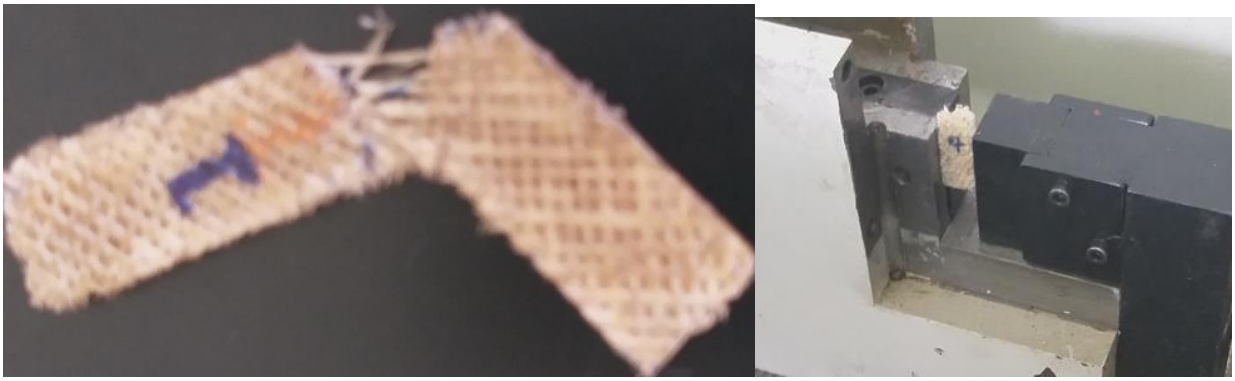

Fig. 26 unseparated test specimen after impact (left) and separated test specimen (right)

But most of a $30^0/60^0$ and 30^0/-45^0 orientation WSFRUPC test specimen completely separated except one $30^0/60^0$ test specimen. This specimen showed relatively higher impact strength (138.59kJ/mm^2) compared to the other $30^0/60^0$ test specimens. While most of the 45^0/-45^0 orientation WSFRUPC test specimens showed an absorbed energy of 1.02Joule and the fiber

holds the two pieces together as shown in figure 26. This shows that 45^0/-45^0 orientation WSFRUPC have greater absorbed energy values than the other WSFRUPC test specimen.

The force displacement curve was plot using discrete data values recorded on a computer and force displacement relationship (figure 27). The force displacement curve shows that until the reaction force reaches its maximum value during impacting instant, there was negligible test specimen displacement. But after the impacting force becomes maximum, the displacement of the specimen increases even though the impacting force decreases due to the absorption of impact energy.

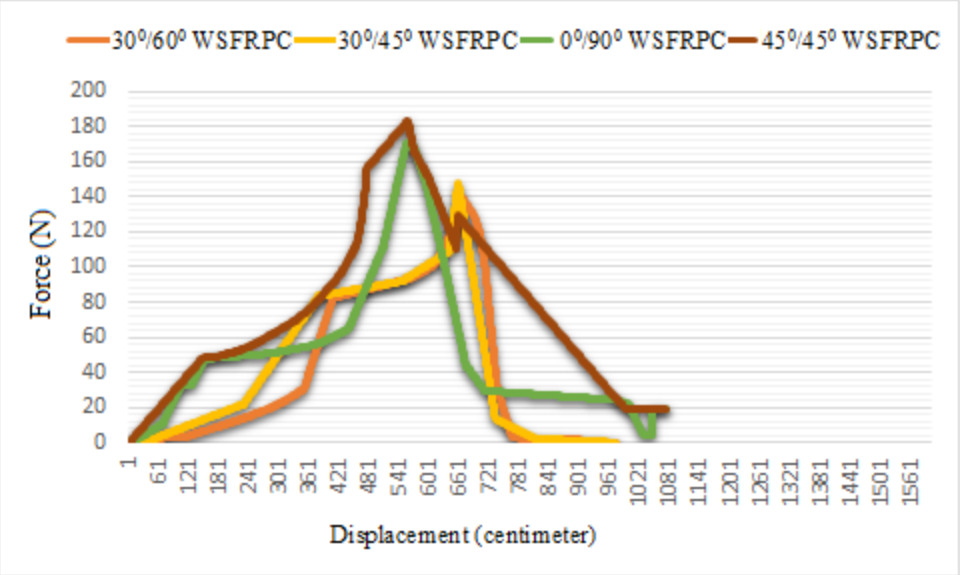

Fig. 27A force versus time curve for average data values

Even though the test conditions and method of composite fabrication are different and is difficult to compare, average ASTM impact strength of a 40% by weight of fiber 45^0/-45^0 WSFRUPC was 342.67 J/m which was about 70J/m greater than the ASTM impact strength of chopped sisal fiber reinforced polyester composite (having impact strength 250-300J/m [15]) manufactured using resin transfer molding. But average ASTM impact strength of a 40% by weight of fiber 30^0/-45^0 WSFRUPC was 261.33J/m which was comparable to ASTM impact strength of chopped sisal fiber reinforced polyester composite manufactured using resin transfer molding. In addition, the result in this investigation showed greater impact strength compared to the impact strength (>200 J/m) of braided woven fabric Jute banana reinforced $0/90^0$ polyester composite [41]. Compared to the impact energy (maximum impact energy 0.8) and impact strength (maximum impact strength 30KJ/m^2) of short fiber sisal fiber reinforced epoxy composite fabricated keeping 30% by weight of fiber and treated with % NaOH solution [30], $0/90^0$ and 45^0/-45^0 test specimen used in this investigation showed greater impact energy and impact strength. When compared to Short randomly oriented bent grass reinforced polyester composite which showed impact strength of 70.86J/m[30] for 40% by volume of fiber (treated with 5%

NaOH concentration), the results from this experimental investigation showed greater impact strength.

Similarly, even though the test conditions, test standard, composite fabrication and fiber form are different, the average ISO impact strength of $30^0/60^0$ WSFRUPC (127.01 KJ/m^2), $30^0/-45^0$ WSFRUPC (137.54 KJ/m^2), $0/90^0$ WSFRUPC (158.94 KJ/m^2), and $45^0/-45^0$ WSFRPC (180.35 KJ/m^2) was less comparable to ISO Charpy impact strength of short randomly oriented sisal fiber reinforced polyester composite (284.1KJ/m^2)[42] fabricated using hand layup and compression molding. This is because the charpy impact test has a slightly different test procedure. In addition all $30^0/60^0$ WSFRPC (average impact strength 127.01 KJ/m^2) $30^0/-45^0$ WSFRUPC (average impact strength 137.54KJ/m^2), $0/90^0$ WSFRPC (average impact strength 158.94 KJ/m^2) and $45^0/-45^0$ WSFRPC (average impact strength 180.35 KJ/m^2) showed greater impact strength than sisal epoxy composite (24.49KJ/m^2[1]) processed using hand layup process. The impact strength result of this experimental investigation on all cases ($45^0/45^0$, $0^0/90^0$, $30^0/60^0$ and $30^0/45^0$ orientations) is greater than the impact strength of short sisal fiber reinforced unsaturated polyester composite which showed impact strength of (3.581Nm) for untreated fiber and impact strength of (1.962Nm) for treated sisal fiber at 6 mm specimen thickness and 30%wt [12]. Woven kenaf fiber reinforced epoxy composite fabricated by hand layup technique (impact strength of arround 10KJ/m^2) with $0/90^0$ orientation and woven kevlar fiber reinforced epoxy composite (impact strength of arround 10KJ/m^2) fabricated using similar procedure was tested by charpy impact test [31]. But the results in this experimental investigation showed greater impact energy. In addition, the impact strength of test specimen used in this experimental investigation was greater than the impact strength of short randomly oriented sisal fiber reinforced epoxy composite (65.63J/m[30]) and the impact strength of unidirectional 0,90,0 sisal fiber reinforced epoxy composite (1.35KJ/m^2[30]). This may be mainly due to woven fiber form used in this study and 40% fiber weight fraction. The Izod impact strength of 5% NaOH solution treated, dried at 70^0c oven, and 100^0c heat treated chopped sisal fiber reinforced polyester composite (40% vol. of fiber) was around 300J/m[15] and compared to this, $0/90^0$ and $45^0/-45^0$ woven sisal fiber reinforced polyester composite treated with 5% NaOH solution showed greater Izod impact energy value (average impact strength of 342.67J/m).

Cross observation of impacted test specimen shows that the mode of failure is more favorable to matrix cracking than fiber breakage and delamination. Because there was no delamination of the test specimen after impact.

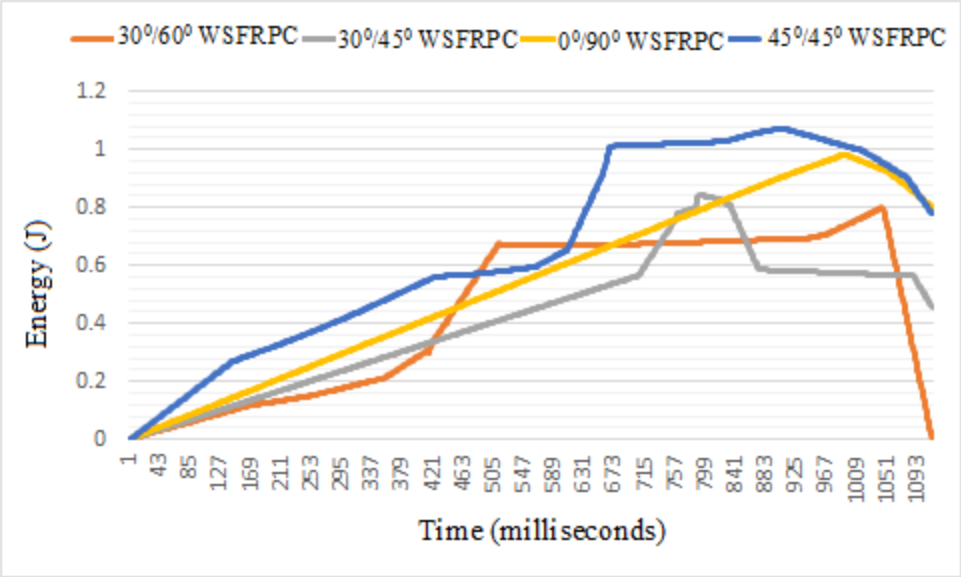

Fig. 28 Energy versus time curve for average data values

In addition it was observed that there was no fiber breakage. Shear yielding of the matrix can be a reason for matrix failure and it may be as a result of applied impact load, presence of impurities in the resin or poor composite lamination. Instead, the fiber bundle holds the two broken pieces together after impact. Matrix cracking can be encountered as a result of poor composite fabrication process (hand layup), fiber bridging or porosity as a result of trapped air. The maximum impacting work that can be done by Izod impact testing machine was 274.08Nm. While the impacting work absorbed by the test specimen can be obtained from energy versus time graph. The area under the energy versus time graph gives the work done on the test specimen due to impacting load. The work done on the test specimen by the impactor knife can also be calculated analytically from the impactor knife movement and the change in rise and falling angle.

$$W = PL(cos\,\beta - cos\,\alpha$$

Where PL is impactor knife movement, α and β are falling and rise angles.

4.1.3. Post impact SEM assessment

The scanning electron microscope was employed to investigate cross-sectional EDS and morphology of sisal fiber reinforced unsaturated polyester composite. Sisal fibers have a quadrate grid pattern on its longitudinal surface [16]. Mercerization of sisal fibers improves the surface properties by removing hemicellulose and lignin present between micro-fibrils resulting in increased tensile properties. The removal of hemicelluloses and lignin, also results in the separation of fibrils. These micro-fibrils can get embedded in the resin in composites and can be expected to improve the interfacial shear strength resulting in the improvement of the composite strength [16]. The SEM was taken on the prepared specimen of the type having greater absorbed energy. Because, with the available SEM set up, it is not convenient to use a specimen of

impacted portion. In this instance, the specimen was Gold coated in its sputtering process to make it conductive.

The 10μm resolution SEM micrograph cross-sectional morphology and elemental detection system result, as shown in figure 29, showed that unsaturated polyester resin yields earlier than the reinforcing sisal fiber. Possibly a number of factors can influence the earlier yielding or failure of the unsaturated polyester resin. Porosity, opening between weft and wrap thread, and matrix deformation can be the main reasons for matrix failure or yielding. Large opening between weft and wrap thread can result matrix failure but small opening between weft and wrap thread may result high crimp effect which in turn results fiber bridging. Optimum opening between weft and wrap threads can minimize matrix failure. Large opening between weft and wrap threads, high crimp effect or fiber bridging and the trapping of air during composite lamination can be a reason for porosity.

When porosity exists in the laminated composite, shear failure or matrix yielding may occur. In addition matrix yielding may occur as a result of matrix deformation due to the applied impact load. The applied impact load can initiate crack in the matrix. As can be seen in figure 30 from SEM micrograph result, crack has propagated along the matrix material. This crack propagation can be a reason for shear failure of the matrix and thus failure of laminated WSFRUPC. Cross sectional morphology and EDS SEM analysis result showed that there is a crack and porosity on the matrix portion of the composite.

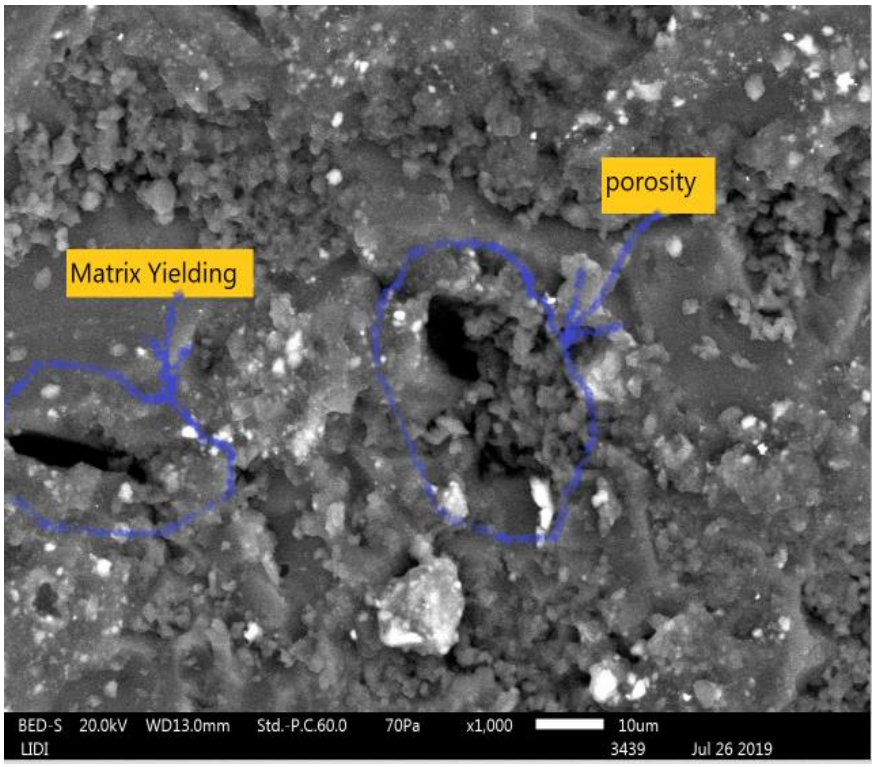

Fig. 29 A 45^0/-45^0 WSFRPC 10μm SEM micrograph

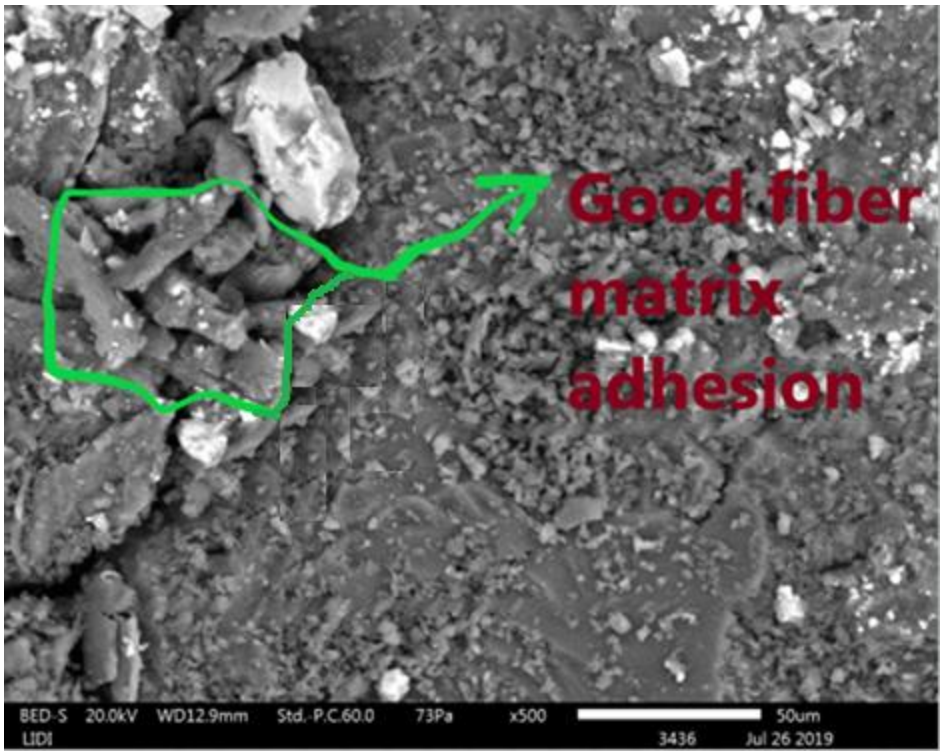

Fig. 30 A $45^0/-45^0$ WSFRUPC 100μm SEM micrograph

The opening between consecutive weft and wrap tows can be a cause for porosity. This porosity can be a reason for crack initiation and composite failure. But matrix deformation due to the applied impact load can be also a reason for matrix yielding and then composite failure.From visual inspection of the impacted test specimen and from the result of SEM micro graph analysis, as shown in figure 30, good fiber matrix adhesion was shown. This good fiber matrix adhesion might be due to good alkali treatment procedure. As a result it can be said that failure of the laminated composite was due to shear failure of the matrix material rather than delamination of the campsite.

Even though fiber breakage is not the primary cause for the failure of this laminated WSFRUPC, it can be seen that on some of the test specimens there was fiber breakage and complete separation of test specimen, as shown in figure 26 (right side). These test specimens that showed fiber breakage and complete separation have comparatively less impact strength. In contrary to these, there were specimens that fiber hardly break, as shown figure 26 (left side), and these test specimens showed comparatively high impact strength.

The 50μm SEM micrograph result, figure 30, showed that there was good adhesion of fiber and matrix during impregnation of each ply. But the crack like structure and the dark line around the fiber thread showed that either there was a delamination (during specimen cutting or due to the applied load) or poor adhesion of resin to the impregnated fiber during composite lamination. Whereas from figure 29 and 30, SEM result showed that there was good adhesion between impregnated fibers and resin. Thus test specimen cutting process for impact testing and test specimen cutting process for SEM analysis may have a residual stress effect.

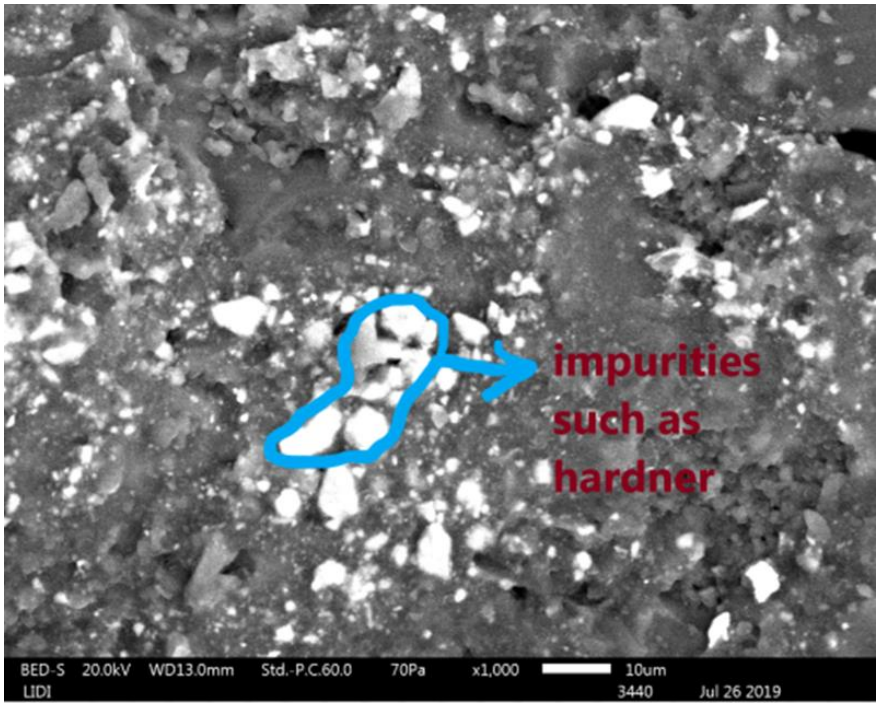

Fig. 31 A $45^0/-45^0$ WSFRUPC 10μm SEM micrograph

4.2. Main findings

Characterization of impact resistance behavior of woven sisal fiber reinforced polyester composite showed that the increased absorbed energy for $0/90^0$ and $45^0/-45^0$ test specimens compared to other $30^0/60^0$ and $30^0/-45^0$ test specimens. A $45^0/45^0$ oriented woven sisal fiber reinforced polyester composite showed better average toughness energy (0.02 J/mm^2) and average absorbed energy (1.03J). It has also showed better average impact strength of 342.67 J/m than other woven sisal fiber reinforced polyester composite used in this study. From all the test specimens used in this experimental study, $30^0/60^0$ WSFRPC showed less average absorbed energy and impact strength compared to other test specimens. Since similar procedure has been followed in the specimen preparation and testing, it can be concluded that $45^0/-45^0$ oriented woven sisal fiber reinforced polyester composite has better impact strength. When compared to previous studies, the test specimens tested in this study showed greater impact energy than non-woven sisal epoxy composite fabricated using hand layup process and tested using Izod impact testing setup. The SEM micrograph analysis result showed that there was a matrix yielding or failure as a result of crack propagation. This crack propagation might be due to the porosity induced in the composite material or shear failure of matrix material as a result of the applied impact load.

Chapter five

5.1. Conclusion

The experimental characterization of impact resistance behavior of $30^0/60^0$, $30^0/-45^0$, $0/90^0$ and $45^0/-45^0$ orientation woven sisal fiber reinforced polyester composite using 40% by weight of sisal fiber was studied. The result showed that the average absorbed energy and impact strength of $0/90^0$ and $45^0/-45^0$ WSFRPC was greater compared to $30^0/60^0$ and $30^0/-45^0$ WSFRPC. Compared to all other orientation test specimens, the $30^0/60^0$ WSFRPC showed less absorbed energy (average absorbed energy 0.72J) and impact strength (average impact strength 241.33J/m). A $45^0/45^0$ oriented woven sisal fiber reinforced polyester composite showed better toughness energy (0.02 J/mm^2) and absorbed energy (average absorbed energy 1.03J). It has also better impact strength (average impact strength 342.67 J/m) than the other orientation woven sisal fiber reinforced polyester composites.

When compared to previous studies, the test specimens tested in this study showed greater impact energy than non-woven sisal epoxy composite fabricated using hand layup process and tested using Izod impact testing setup. In addition, when compared to the impact strength of jute-banana hybrid $0/90^0$ woven composite (about 200J/m) tested with Izod impact testing machine of un-notched specimen using ASTM D256 standard, the results of this experimental investigation for all type of orientation showed greater impact strength.

Thus, the results of this experimental investigation showed that a $45^0/-45^0$ oriented woven sisal fiber reinforced polyester composite can be used as a semi-structural material. Therefore the importance of this study is to show the impact strength of WSFRUPC so that the user can select this composite in a structural application they need.

In future work, woven sisal fiber can be hybridized with a filler natural fiber such as bamboo powder in order to fill the opening area between wefts and wrap fiber bundles and increase impact strength of the composite.

5.2. Recommendation

In this study the experimental characterization of impact resistance of woven sisal fiber reinforced unsaturated polyester composite has been carried out using ASTM D256 standard and Izod impact testing set up. In addition, SEM analysis of woven sisal fiber reinforced polyester composite has been carried out. Four types of woven sisal fiber reinforced polyester composite ($30^0/60^0$, $30^0/-45^0$, $0/90^0$ and $45^0/-45^0$) of 40% fiber weight fraction was experimentally investigated. The experimental results showed that $45^0/-45^0$ woven sisal fiber reinforced polyester composite has an average impact strength of 342.67J/m and $0^0/90^0$ woven sisal fiber has average impact strength of 302J/m. From these results the following points are recommended.

1) Woven sisal fiber reinforced polyester composite of $45^0/-45^0$ orientation has comparable impact strength and toughness with other natural fiber reinforced polymer composites such as kenaf, jute and ramie. It also has comparable strength to glass fiber reinforced polymer composite. Therefore the $45^0/-45^0$ orientation woven sisal fiber reinforced polyester composite of is recommended to be used as a semi-structural material.

5.3. Future work

In this study, the experimental characterization of impact resistance behavior of $30^0/60^0$, $30^0/-45^0$, $0/90^0$ and $45^0/-45^0$ orientation woven sisal fiber reinforced polyester composite was carried out. The result showed that the average absorbed energy and impact strength of $0/90^0$ and $45^0/-45^0$ WSFRPC was greater compared to $30^0/60^0$ and $30^0/-45^0$ WSFRPC. Woven sisal fiber reinforced polyester composite studied in this experimental investigation has comparable impact strength and toughness with other natural fiber reinforced polymer composites such as kenaf, jute and ramie. It also has comparable strength to glass fiber reinforced polymer composite. And these days, due to environmental concerns, there is a need to replace synthetic composite materials by natural and biodegradable materials. But the impact strength of woven sisal fiber reinforced polyester composite has limited its application to semi-structural application.

Therefore in future, woven sisal fiber can be hybridized with a filler natural fiber such as bamboo powder in order to fill the opening area between wefts and wrap fiber bundles and increase impact strength of the composite.

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Appendix

Fig. APPEX 1 sisal in the field that Ethiopians farmers used to produce fiber

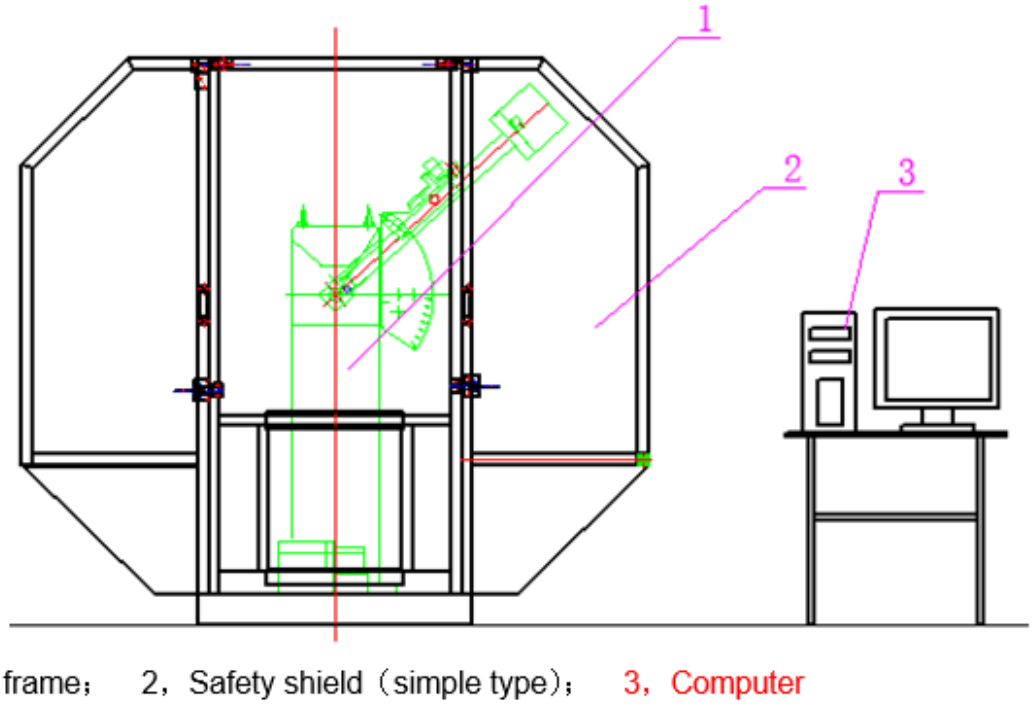

Fig. APPEX 2 B1JWT-406DI impact testing set up consists of load frame, computer controller and safety shield.

Fig. APPEX 3 B1 A$45^0/45^0$ specimen number one clamped on Izod anvil

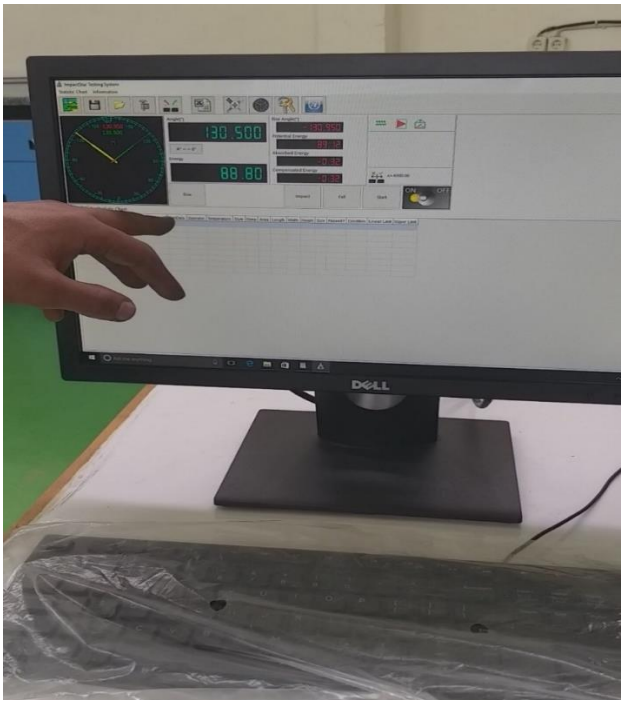

Fig. APPEX 4 Results displayed using a computer integrated to Izod impact test set up

Table APPEX 5 Tabular results of impact test for 40% volume fraction $30^0/60^0$ WSFRUPC specimen

Item No.	Specimen	Orientation	Impact speed (m/s)	Toughness (J/mm^2)	Absorbed Energy (J)	Notch area (mm^2)	Specimen thickness (m)	ASTM Impact strength (J/m)	ISO Impact strength (KJ/m^2)
1	1	$30^0/60^0$	5.25	0.01	0.64	5.7	0.003	213.33	112.28
2	2	$30^0/60^0$	5.25	0.01	0.78	5.7	0.003	260	136.84
3	3	$30^0/60^0$	5.25	0.01	0.71	5.7	0.003	236.67	124.56
4	4	$30^0/60^0$	5.25	0.01	0.70	5.7	0.003	233.33	122.81
5	5	$30^0/60^0$	5.25	0.01	0.79	5.7	0.003	263.33	138.59

Table APPEX 6 Tabular results of impact test for 40% volume fraction $30^0/45^0$ WSFRUPC specimen

Item No.	Specimen	Orientation	Impact speed (m/s)	Toughness (J/mm^2)	Absorbed Energy (J)	Notch area (mm^2)	Specimen thickness (m)	ASTM Impact strength (J/m)	ISO Impact strength (KJ/m^2)
1	1	$30^0/45^0$	5.25	0.01	0.84	5.7	0.003	280	147.36
2	2	$30^0/45^0$	5.25	0.01	0.75	5.7	0.003	250	131.57
3	3	$30^0/45^0$	5.25	0.01	0.78	5.7	0.003	260	136.84
4	4	$30^0/45^0$	5.25	0.01	0.77	5.7	0.003	256.67	135.09
5	5	$30^0/45^0$	5.25	0.01	0.78	5.7	0.003	260	136.84

Table APPEX 7 Tabular results of impact test for 40% volume fraction $0^0/90^0$ WSFRUPC specimen

Item No.	Specimen	Orientation	Impact speed (m/s)	Toughness (J/mm^2)	Absorbed Energy (J)	Notch area (mm^2)	Specimen thickness (m)	ASTM Impact strength (J/m)	ISO Impact strength (KJ/m^2)
1	1	$0^0/90^0$	5.25	0.01	0.84	5.7	0.003	280	147.36
2	2	$0^0/90^0$	5.25	0.02	0.97	5.7	0.003	323.33	170.18
3	3	$0^0/90^0$	5.25	0.01	0.96	5.7	0.003	320	168.42
4	4	$0^0/90^0$	5.25	0.02	0.98	5.7	0.003	326.67	171.93
5	5	$0^0/90^0$	5.25	0.01	0.78	5.7	0.003	260	136.84

Table APPEX 8 Tabular results of impact test for 40% volume fraction $45^0/45^0$ WSFRUPC specimen

Item No.	Specimen	Orientation	Impact speed (m/s)	Toughness (J/mm^2)	Absorbed Energy (J)	Notch area (mm^2)	Specimen thickness (m)	ASTM Impact strength (J/m)	ISO Impact strength (KJ/m^2)
1	5	$45^0/45^0$	5.25	0.02	1.02	5.7	0.003	340	178.95
2	6	$45^0/45^0$	5.25	0.02	0.98	5.7	0.003	326.67	171.92
3	7	$45^0/45^0$	5.25	0.02	1.05	5.7	0.003	350	184.21
4	8	$45^0/45^0$	5.25	0.02	1.02	5.7	0.003	340	178.95
5	9	$45^0/45^0$	5.25	0.02	1.07	5.7	0.003	356.667	187.72