FABRICATION AND DETERMINATION OF MECHANICAL PROPERTIES OF WOVEN SISAL FABRIC REINFORCED EPOXY COMPOSITES

BY

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DECLARATION

DECLARATION BY STUDENT

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DEDICATION

To

My Father Mr. Bichang'a;

My Late Mother Mrs. Winfiridah Kerubo;

Celestina Bosibori;

Martha Biyaki;

Mercyline Barongo;

Daphine Nyanduko;

Cynthia Moraa;

For Continual Love, Support & Encouragement

ABSTRACT

Engineering materials manufactured from synthetic fibres are responsible for global environmental pollution since they are non-biodegradable. Sisal natural fibers provide a better alternative as they are sustainable, biodegradable, inexpensive and available worldwide. Kenya produces over 28,000 metric tonnes of sisal fibres annually which is exported in raw form. The use of sisal fibres in composites fabrication will add value to the locally produced sisal. This will replace products currently manufactured from plastics and wood. This will create job opportunities, reduce environmental pollution and conserve the forests. The objectives of this research were to investigate the properties of woven sisal fabric reinforcement, fabricate woven sisal fabric reinforced epoxy composite, analyze the effect of fibre weight fraction (v_{wf}) and alkali treatment on the mechanical properties of the resultant composites and evaluate the mechanical (i.e. compression, tensile, impact and flexural) properties of woven sisal fabric reinforced epoxy composites. The method used in this research was experimental study whereby sisal fibre composites were fabricated by reinforcing epoxy resin with woven sisal fabric using hand lay-up technique. A mould measuring 310 x 310 x10 mm was fabricated in the School of Engineering Workshop and thoroughly cleansed. A mould release agent was applied on the mould surface before placing the weighed sisal fabric layers. The required quantity of the epoxy matrix was applied uniformly on the sisal fabric and the composites were allowed to cure at temperature of 23^0C for 24-hours under a mass of 30kg (3.3kN/m^2 compressive pressure) that ensured uniform consolidation of the material. To investigate the effect of alkali treatment on the mechanical properties of the resultant composites, some fibres were soaked in 4% w/v NaOH solution for one hour followed by oven pre-drying at 80^0C for another one hour before using them in composite fabrication (alkali treated samples) while other fibres were directly used without any surface modification (untreated/control samples). The fibre weight fraction for both treated and untreated composites samples was varied at 30, 40, 45, 50 and 60% using Central Composite Rotatable Design (CCRD) design of experiment Specimens for mechanical testing were prepared based on ASTM D638, ASTM D3410, ISO 179:1997 and ASTM D790 standards. Use of tables and bar charts was made in the analysis of data. The results showed that sisal woven reinforcement sustained higher tensile loads when tested along the warp direction than in the weft direction. The mechanical properties of alkali treated composites were found to be higher than untreated composites at the same fibre weight fraction. In both cases, the mechanical properties increased with increasing fibre weight fraction (V_{wf}). The tensile and compressive strengths increased from 22.63MPa to 30.91MPa and 15.32MPa to 23.91MPa respectively as fibre loading increased from 30%V_{wf} to 50%V_{wf}; flexural strengths increased from 19.17MPa at 30%V_{wf} to 27.16MPa at 60%V_{wf}; impact strength increased from 17.89KJ/m^2 at 30%V_{wf} to 24.58KJ/m^2 at 45%$V_{wf.}$ The mechanical properties studies in this research show that the composites are strong enough to meet the essential requirements for non-structural applications such as ceiling boards and wall partitioning materials. Future research should study the physical properties such as water absorption and burning test of the sisal woven epoxy reinforced composites as well as cost analysis.

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LIST OF ABRREVIATION AND ACRONYMS

ASTM	American Standard for Testing and Materials
CCRD	Central Composite Rotatable Design
GPa	Giga Pascal (10^9)
HDPE	High Density Polyethylene
ISO	International Standards Organization
KPa	Kilo Pascal (10^3)
LDPE	Low Density Polyethylene
MPa	Mega Pascal (10^6)
MRA	Mould Release Agent
NaOH	Sodium Hydroxide
PE	Polyethylene
PET	Poly (ethylene terephthalate)
PP	Polypropylene
PS	Polystyrene

CHAPTER ONE: INTRODUCTION

1.1 Background of the Study

Composites are engineered materials made of at least two constituents with significantly different physical or chemical composition bonded together while retaining their individual identities and properties within the finished structure. Due to increased environmental concerns and awareness, natural fibre reinforced composites are replacing synthetic fibre reinforced composites in mostly non-structural applications. Natural fibres such as coir, banana, jute, sisal among others are light-in-weight, low cost, non-toxic, naturally available, renewable and biodegradable in nature. Composites from these fibres have gained importance in many non-structural applications such as room partitions, door panels and food packaging due to their resistance to corrosion and chemicals, light-weight and unique functional properties such as damping, low electrical and thermal conductivity (Bledzk & Gassan, 1999; Netravali & Chabba, 2003).

Sisal fibres obtained from sisal plant (*Agave Sisale*) are widely used natural fibres. These fibres are extracted from the periphery of the leaf by decortication and retting processes. Sisal fibres are cheap, biodegradability and readily available (see Table 1.1). However, they have major bottlenecks such as incompatibility with some polymeric matrices, poor wettability and high moisture absorption (Vazguez, Riccieri, & Carvalho, 1999). Several research works have been carried out to overcome these challenges and hence improve the fibre/matrix interfacial adhesion. Research findings have shown the effect of fibre treatment, both physical and chemical on the mechanical properties of sisal reinforced polymer composites. For instance, heat treatment tends to improve the crystallinity of the fibre thus the stiffness of the final composite is improved. Alkali treatment on the other

hand, eliminates hemicelluloses and lignin part thereby increasing cellulose content and fibrillation (Sreekumar et al., 2009).

Table 1.1: Comparison between synthetic and natural fibres (Wambua et al., 2003)

	Properties	Natural fibres	Glass fibres	Carbon fibres
Economy	Annual global production (tonnes)	7.2 million	600,000	120,000
	Cost of raw fibre (USD/kg)	Low (0.35-2.5)	Moderate (1.3-3.5)	High (>16)
Technical	Density (g/cm^3)	Low (1.35-1.55)	High (2.5-2.7)	Moderate (1.7-2.2)
	Tensile stiffness (GPa)	Moderate (30-80)	Moderate (70-85)	High (150-500)
	Tensile strength (GPa)	Low (0.4-1.5)	Moderate (2-3.7)	High (1.3-6.3)
	Tensile failure strain (%)	Low (1.4-3.2)	High (2.5-4.3)	Low (0.3-2.2)
Ecological	Energy demand of raw fibre (MJ/kg)	Low (4-15)	Moderate (30-50)	High (>150)
	Renewable source	Yes	No	No
	Recyclable	Yes	Partially	Partially
	Biodegradable	Yes	No	No
	Hazardous/toxic (upon inhalation)	No	Yes	Yes

In addition to fibre surface modification, other factors such as weight fraction, fibre length, fibre orientation, fibre/matrix interfacial adhesion and curing cycle affect the mechanical properties of sisal reinforced polymer composites. For example, application of high pressure before the gel point temperature during curing cycle results into high

impact strength as a result of higher matrix diffusion. On the other hand, there is reduced number of voids in the composites when a higher final pressure is applied at the point matrix cure (Jackson et al., 2009).

1.2 Statement of the Problem

In Kenya, high volumes of plastic wastes are dumped in most urban centers due to the polymer's preferred usage in packaging, ceiling materials and other applications. These plastics pose a serious threat of environmental degradation such as clogging of water drainage system, land degradation and air pollution when burned. Attempts to recycle these wastes have faced serious challenges due to non-biodegradable nature of these plastics thereby making land disposal most unattractive. The current research aims at addressing the current scenario by developing environmental friendly sisal reinforced composites to replace products currently manufactured from plastics and wood. The use of sisal fibre reinforcement is attractive to the environment since it is characterized with carbon neutrality (when burned), compostability and ease of incineration.

1.3 Justification of the Research

Sisal fibres have the highest world availability. For instance the global availability of sisal is estimated at 600,000 tonnes against 100,000 tonnes and 28,200 tonnes for banana and coir fibres respectively. Kenya produces over 28,000 metric tonnes of sisal fibres annually which is exported in raw form. Sisal fibres have high mechanical properties due to high lignocellulose content of 84% compared to 69% for banana fibres (Mwaikambo and Ansell, 2002). Also, epoxy matrix undergoes a cross-linking reaction forming strong chemical bonds that cannot re-melt on heat application suitable for high-heat applications. Therefore, the production sisal based composites will add value to the

locally produced sisal. This will create job opportunities, reduce environmental pollution and conserve the forests.

1.4 Objectives of the Study

1.4.1 General Objective

To fabricate and determine the mechanical properties of woven sisal fabric reinforced epoxy composites.

1.4.2 Specific Objectives

The specific objectives of the research are to:

i. Investigate the properties woven sisal fabric reinforcement.
ii. Produce woven sisal fabric reinforced epoxy composite using hand lay-up technique.
iii. Study the effect of fibre weight fraction (v_{wf}) and alkali treatment on the mechanical properties of the woven sisal fabric reinforced epoxy composites.
iv. Evaluate the mechanical (i.e. compression, tensile, impact and flexural) properties of woven sisal fabric reinforced epoxy composites.

1.5 Methodology

Characterization of sisal woven fabrics by evaluating the tensile properties, production of composites by the use of hand lay-up technique using woven sisal fabric as a reinforcement, epoxy resin and curing agent/hardener and determination of mechanical properties of resultant composites

1.6 Scope of the Study

This research study is limited to fabrication of sisal reinforced epoxy composites and determination of their mechanical (i.e. compression, tensile, impact and flexural) properties.

1.7 Significance of the Study

The study will inform the potential of using sisal fibre reinforced epoxy composites in applications such as furniture, packaging, ceiling and wall partitioning. This is because sisal is biodegradable, renewable and environmentally friendly. Secondly, the fabrication of sisal reinforced epoxy composites on industrial-scale will maximize the benefits of the natural fibre industries that are already in existence. This will result into development of the entire production chain for these industries in addition to job creation for youths and women who will be involved in growing and processing of sisal fibres, design and manufacturing of the composites.

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

The growing environmental concerns and commitment to reduce greenhouse gas (GHG) emissions has increased demand for biodegradable and recyclable materials. There is therefore increased focus on environmentally friendly materials by material scientists aimed at addressing these environmental concerns. Though traditionally these materials have been utilized in non-structural applications, there has been intensive research work geared towards developing natural fibre composites for structural applications (Cheung et al., 2009).

2.2 Sisal Fibre

Sisal is a natural vegetative fibre obtained from the leaves of *agave sisalane* plant and considered one of the widely used natural fibres in the world. The fibre is easily cultivated and has short renewal times. The use of sisal fibres has rapidly increased in the recent past due to an increasing awareness of eco-friendly materials. There are two methods of sisal fibre extraction: retting followed by scrapping and mechanical means using decorticators. Retting method yields a large quantity of poor quality fibres while decortication yields high-quality lustrous fibres at 15 kg per 8 hours. The sisal fibre accounts for over half the total production of plant fibre. The major producers of sisal in the world are Tanzania and Brazil (FAOSTAT, 2016).

Sisal is a smooth, straight fibre measuring 200-400μm diameter and 1-1.25m length. It is easily degraded in alkaline solution. The tensile properties vary along its length with fibres extracted from the lower part having lower tensile strength and modulus but higher

fracture strain. The fibre gets stronger and stiffer at the mid-span with those fibres extracted from the tip showing moderate properties (Chand and Hashmi, 1993).

The schematic cell wall of sisal fibre has several layers of fibrillar structure made of fibrallae (see Fig. 2.1). The structure consists of outer secondary wall (S_1) located within the primary wall where the fibrillae are arranged in spiral at a spiral angle of 40^0 to the cell longitudinal axis while they are sharper in the inner secondary wall (S_2) at an angle of 18-25^0. The lumen is enclosed by the thin, innermost, tertiary wall with a parallel fibrillar structure. These fibrillae are made-up of micro-fibrillae of thickness approximately 20nm which are composed of cellulose molecular chains of 0.7nm thickness (Gram, 1983).

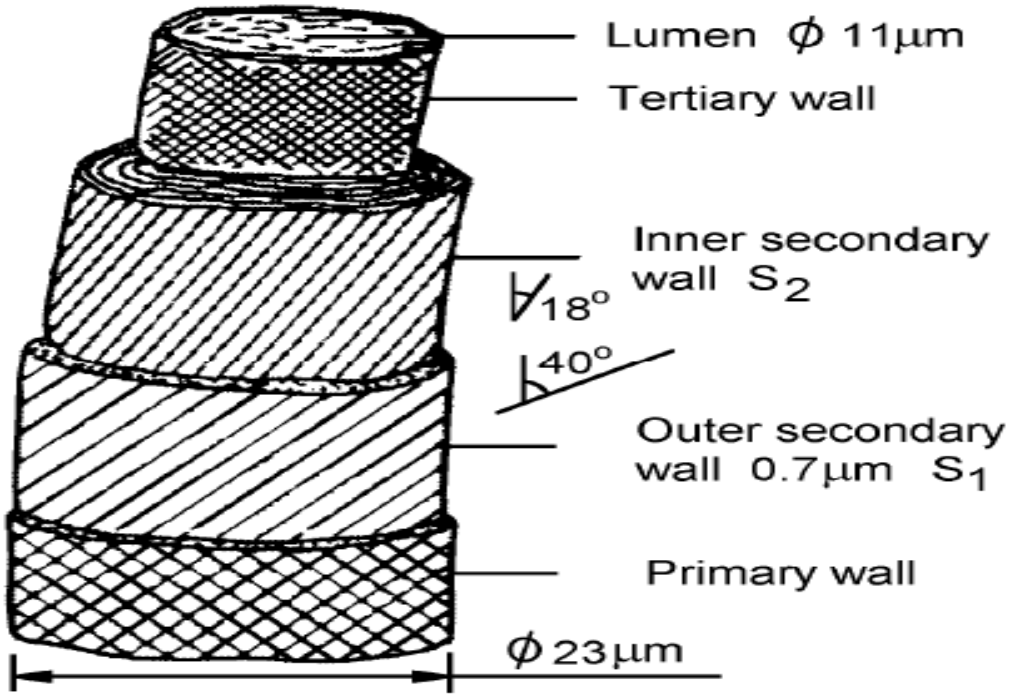

Figure 2.1: Schematic sketch of a sisal fibre cell (Gram, 1983)

The thickness of secondary wall (S_2), with highest cellulose content, and the spiral angle which the bands of microfibrils in the inner secondary cell wall make with the fibre axis

determine the strength and stiffness of plant fibres. Dam, (2009) summarized the properties of Sisal Fibre as:

i. Exceptionally durable with a low maintenance and minimal wear and tear.

ii. It is recyclable.

iii. Anti-static i.e. it does not attract or trap dust particles and does not absorb moisture or water easily.

iv. Easy to dye as a result of fine texture thereby providing the largest range of dyed colours among natural fibres.

v. Good impact and sound absorbing properties.

Table 2.1 gives a comparison between sisal fibres and other natural fibres with respect to mechanical properties, cost, density and world availability.

Table 2.1: Characteristics of different natural plant fibres (Mwaikambo and Ansell, 2002)

	Sisal	Banana	Pineapple	Coir	Cotton
Density (gcm^{-3})	1.5	1.35	1.07	1.2	1.5
Cost (USD/kg)	0.6-0.7	0.9-1.1	0.35	-	_
World availability (tonnes)	600,000	100,292	_	28,200	_
Lignocellulose (%)	84	69	77	79	_
UTS (MPa)	511-635	700-780	360-749	106-175	500-880
Toughness (MPa)	1250	816	970	3200	_
Elongation (%)	7.2	3.0	2.4	25.0	_

2.2.1 Sisal Farming

2.2.1.1 Sisal Farming in the World

In the world, sisal is grown in many countries especially the tropical countries with Brazil and Tanzania being the leading producers. According to Food and Agricultural

commodities production (2016), the global production of sisal in the year 2013 was approximately 270 thousand metric tonnes (see Table 2.2)

Table 2.2: Sisal production in the World in 2013 in '000 metric tonnes (FAOSTAT, 2016)

Country	Brazil	Tanzania	Kenya	Madagascar	China	Mexico	Haiti	Total 269.9
Production /year	150.6	34.9	28.0	18.9	16.5	12.0	9.0	

2.2.1.2 Sisal Farming in Kenya

Agave sisalane is the main sisal variety grown in Kenya. This is because the variety is hard, resistant to water logging and diseases. Most sisal plantations are located in the Coastal, Rift Valley and Central regions with some patches across the country such as Gwassi and Suba districts in Migori County (see Table 2.3).

Table 2.3: Sisal growing regions/areas in Kenya (Sisal Board of Kenya, 2004)

Sisal plantations/estates	Location	Annual Production (Metric tonnes)
REA vipingo plantations	Vipingo-Mombasa	5,000
Taru estate	Mombasa	-
Voi estate	Voi	-
Teita estates	Mwatate	8,700
Dwa estates	Kibwezi	7,000
Mogotio estate	Mogotio	3,000

In Kenya, sisal fibres are extracted through decortication process whereby the leaves are crushed, beaten and brushed away using rotating wheel comprising of blunt knives to

ensure the fibres remain. The fibres are properly sun-dried to required moisture content. This is important as fibre quality is dependent on moisture content. Dry fibres are then brush cleaned, combed and sorted into various grades and then baled for exportation. According to Sisal Board annual report, (2004) about 80% of sisal fibre produced in Kenya is exported to countries such as Spain, Morocco, Saudi Arabia, Belgium, Australia etc. while the remaining 20% is processed in cordage and cottage industries to make products for local market such as coffee bags used to export coffee.

2.3 Matrix System

Composite materials contain a reinforcement that is embedded in the matrix system. The physical and mechanical properties of composite materials depend on the properties of the fibre-matrix interface. In composites, the matrix phase binds the reinforcement together thereby acting as a transmission and distribution medium for externally applied stress to the reinforcement material. This is because a small amount of the applied load is sustained by the matrix phase (Mathews & Rawlings, 1999).

Other functions of the matrix phase are to (Mathews & Rawlings, 1994):

i. Protect the individual fibres from surface damage as a result of mechanical abrasion or chemical reactions with the environment. This may introduce surface flaws that may cause crack resulting into failure at low tensile stress levels.
ii. Disperse the fibres and maintain the required fibre orientation and spacing.
iii. Be thermally and chemically compatible with the reinforcement.
iv. Separate the fibres and, by virtue of its relative softness and plasticity, prevents the propagation of brittle cracks from fibre to fibre, hence acting as a barrier to crack propagation.

There are two main types of polymer resin: thermoplastic and thermosetting.

2.3.1 Thermoplastic Polymer Resins

Thermoplastic polymers are families of linear, branched or cross-linked materials synthesized by polymerisation or polycondensation of monomers. The monomers are reactive materials with low molecular weight. Thermoplastic resins are characterized by reversible processes of softening and hardening on heating and cooling respectively without any noticeable effect on material properties. Examples are polyethylene (PE), polypropylene (PP), polyamide (PA6) and poly(ethylene terephthalate) (PET). Thermoplastics may be recycled by heating, forming and cooling, though the recycled products might show reduced mechanical properties probably due to the reduced molecular weight. Their properties such as strength and high molecular weight are determined by the molecular structure. The weak Van der Waals forces that hold the long chains together are easily broken down by effects of pressure and temperature. Cooling causes the material to solidify again and this is the basis for the current processing techniques for thermoplastics. They exhibit either semi-crystalline or amorphous forms with crystallization occurring during cooling of the molten thermoplastic polymer (Mercier, Zambelli & Kurz, 2002). Due to low cost and versatility compared to thermosets, thermoplastics have been widely used in composites engineering. Their main advantages and disadvantages are summarized in table 2.4.

Table 2.4: Main advantages and disadvantages of thermoplastic resins

Advantages	Disadvantages
Recycling through simple mechanical and thermal methods	Poor impregnation due to high viscosity
Fast processing cycles	High cost of high-performance thermoplastics
Ease of storage	
High toughness	

2.3.2 Thermosetting Polymer Resins

Thermosets are polymers with cross-linked three-dimensional chain structures. They undergo an irreversible chemical cross-linking process formation of tightly bound three-dimensional network of polymer chain. When cured, thermosets cannot be converted back to liquid on heating. Epoxy, unsaturated polyester, vinyl ester, and phenolic are the commonly and most used thermosetting matrices. The cross-linking process imparts hardness, strength, stiffness, brittleness and better dimensional stability to polymers; hence acquiring higher bond strength and hardness making them withstand high temperatures or higher rates of deformation.

(a) Features of epoxy resin

Epoxy resin has the following characteristics:

i. It is clear liquid with long chain molecular structure with two aromatic rings at the centre and two epoxy groups at the ends (see Fig. 2.2).
ii. It has ability to absorb mechanical and thermal stresses due to the presence of aromatic rings at the centre hence good stiffness, toughness and heat resistance properties.

iii. Based on the curing agent, epoxy resin can cure at any temperature between 5^0C - 150^0C.

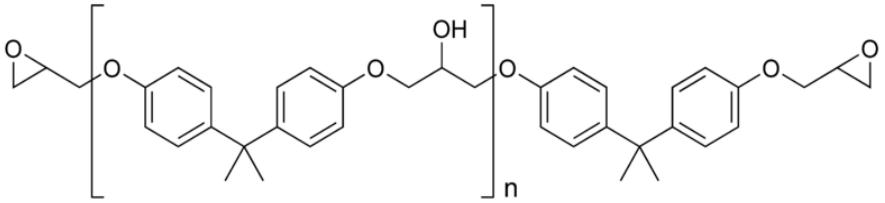

Figure 2.2: Epoxy chemical structure (Luft, 2001)

The main advantages and disadvantages of epoxy resin are summarized in table 2.5.

Table 2.5: Advantages and disadvantages of epoxy resin

Advantages	**Disadvantages**
High water resistance	Expensive
High electrical insulation	High viscosity
Resistance to environmental degradation	Corrosive handling
High thermal and mechanical properties	Critical mixing
High chemical resistance	
Low cure shrinkage	

2.4 Composite Manufacturing Techniques

There are various techniques used in composite manufacturing each having distinct characteristics and suitability. They include: hand lay-up, vacuum bagging, filament winding, resin transfer, pultrusion, infusion process, prepreg moulding, low-temperature prepreg, resin film infusion and spray lay-up.

2.4.1 Hand Lay-up

This method is characterized by low production volume, low investment capital, versatility and labour intensiveness hence mostly suited for large components such as ship, wind turbine and boats. The process involves manual positioning of the reinforcement in an open mould, pouring a resin followed by the action of brush and pressure rollers/squeegees to impregnate the matrix into the reinforcement structure and remove any entrapped air (see Fig. 2.3).

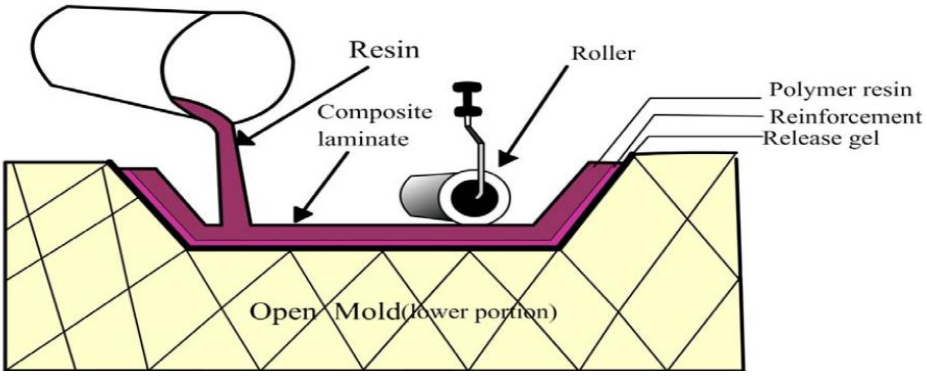

Figure 2.3: Hand lay-up method

The process is mostly used with room temperature curing epoxies and polyester matrix resins where curing takes place within 24 hours. To facilitate the curing process, resin is mixed with a catalyst (also known as curing agent or hardener) which hardens the fibre reinforced resin composite without any external application of heat. To facilitate high part quality and final removal of the composite part surface, mould release agent and a gel coat are first applied to the mould surface. The main advantages and disadvantages of the Hand-layup method are summarized in Table 2.6.

Table 2.6: Advantages and disadvantages of the hand-layup method

Advantages	**Disadvantages**
Design flexibility.	Only one molded surface is obtained.
Large and complex items can be produced.	The skills of the operator determine the quality of the final product.
Tooling cost is low.	Low volume process.
Easy to effect any design changes.	Longer cure times required.
Sandwich constructions are possible.	The waste factor can be high.
Compatible with longer fibres as well as higher fibre content compared with spray lay-up.	Resins need to be low in viscosity to be workable by hand.
Semi-skilled workers are needed.	

2.5 Factor Affecting the Mechanical Properties of Sisal Fibre Reinforced Composites

Combinations of various factors influence the mechanical properties of sisal reinforced composites. The main factors include: fibre and matrix properties, fibre volume fraction and interfacial strength.

2.5.1 Properties of the Reinforcing Material

The major fibre properties affecting the mechanical behavior of composites include: fibre dispersion, fibre aspect ratio and fibre orientation. There should be good fibre dispersion to ensure that the fibres are separated from one another hence no clumps and agglomerates as well as each fibre is being surrounded by the matrix. Insufficient fibre dispersion causes heterogeneous resin-rich and fibre-rich regions. This scenario is undesirable in composites as the resin-rich regions tend to be weak because they are vulnerable to micro-cracking resulting into inferior composite mechanical properties. To achieve maximum mechanical properties of the composites, there should be

homogeneous fibre dispersion. Fibre dispersion in composites is governed by two factors: fibre-fibre interaction (strong hydrogen bonding between the fibres) and fibre length (Alvarez, Ruscekaite, & Vazquez, 2003).

The mechanical properties of fibre reinforced polymer composites are also affected by the orientation of fibre reinforcement in the composites. The influence of fibre orientation on composite mechanical properties has been investigated by Kuruvilla et al., (1999). In this study, the tensile strength of the composite with fibre in parallel direction was 20-40% higher than those in perpendicular direction.

2.5.2 Fibre and Matrix Volume (or Weight) Fractions

The proportions and properties of fibre and matrix in the composite affect not only the properties but also fabrication techniques of composites. The proportions can be expressed in two ways:

i. As weight fraction (W) which is relevant to fabrication. This relates the weight of constituents to composite weight.

ii. As volume fraction (V) which is commonly used in property calculations. This relates the volume of the constituents to the volume of the composite.

The fibre volume fraction V_f may be expressed in terms of fibre weight fraction, W_f, as:

$$V_f = \frac{\rho_m W_f}{\rho_m W_f + \rho_f W_m} \quad \text{.....(2.1)}$$

The relationship between fibre volume fraction and weight fraction is given by;

$$W_f = \frac{\rho_f V_f}{\rho_f V_f + \rho_m V_m} \quad \text{.....(2.2)}$$

Where ρ_m and ρ_f are matrix and fibre densities respectively, W_m and V_m are matrix weight and volume fractions respectively.

The effect of fibre loading (either as weight or volume fraction) on composites' mechanical properties has been investigated by Girisha et al., (2012). They deduced that fibre loading up to a certain limit was directly proportional to the composites' mechanical properties. The results of sisal/coir epoxy polymer composites indicated that on increasing fibre loading (weight), there was a corresponding increase in the tensile and flexural strength of the composites (see Fig. 2.4).

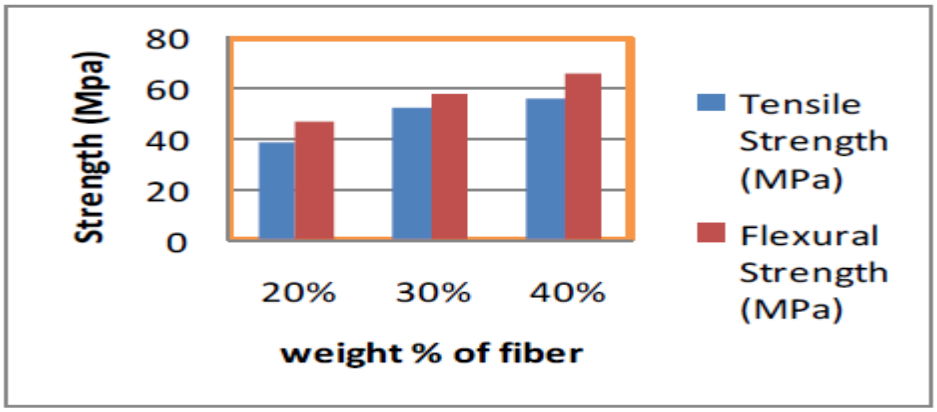

Figure 2.4: Effect of fibre content on tensile and flexural strength of sisal/coir epoxy composites (Girisha et al., 2012)

2.5.3 Fibre-matrix Interface

This affects the efficiency of the transfer of load from the matrix to the fibres and therefore the properties of the composite in directions transverse to the fibres when they are aligned. It also ensures reduced rates of degradation of the composite in aggressive environments. It is important to note that the contribution of the fibres and the matrix to the average composite properties are proportional to their volume fractions as explained by the rule of mixtures for the elastic modulus (see Eqn. 2.3);

$$E_c = E_f V_f + E_m V_m \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.3)$$

and in general, $X_c = X_f V_f + X_m V_m$ where X_c represents an appropriate property of the composite.

2.5.4 Fibre Treatment

Natural fibres are mainly made of cellulose, hemicellulose, lignin, pectin, waxes and water soluble substances. Cellulose contains hydroxyl group giving natural fibres hydrophilic properties when used with hydrophobic matrices thereby resulting in very poor fibre-matrix interface and poor resistance to water absorption. Therefore, various fibre surface modifications such as mercerization, acetylation, silane and isocyanate treatments are done to reduce the water sorption characteristics of natural fibres and improve the bond between the fibres and the matrix (Thomas & Sreekala, 2003).

2.5.4.1 Alkali Treatment

Alkali treatment of natural fibres disrupts the hydrogen bonding in the network structure. This is done using sodium hydroxide (NaOH), Lithium hydroxide (LiOH) and Potassium hydroxide (KOH) solutions. In most cases, NaOH is used to remove the lignin-containing materials, natural oils, waxes and pectin. In alkali treatment, fibres are immersed in NaOH solution of a given concentration for a given period. The alkali reaction can be expressed as:

Cellulosic Fibre – OH + NaOH $\longrightarrow$ Cellulosic Fibre – O^-Na^+ + H_2O

This treatment serves to increase surface roughness resulting in better mechanical interlocking between fibres and improves the percentage of cellulose exposed on the fibre surface thus increasing the number of possible reaction sites (Valadez-Gonzalez et al., 1999). The effect of NaOH concentration on sisal fibre reinforced composites using 0.5,

1, 2, 4 and 10% NaOH concentration has been investigated. It was observed that the maximum tensile strength resulted from 4% NaOH treatment at room temperature. This is because, at higher alkali concentration, there is excess de-lignification of natural fibres resulting in weaker or damaged fibres. The tensile strength of the composites decreased drastically from the optimal value (Jacob, Thomas, & Varughese, 2004).

2.5.4.2 Silane Treatment

Silane (SiH_4) is used as a coupling agent to allow natural fibres adhere to a polymer matrix thus stabilizing the composite materials by reducing the number of cellulose hydroxyl groups in the fibre-matrix interface. In the presence of moisture, hydrolysable alkoxyl groups cause the formation of silanols. Stable covalent bonds are formed with cellulosic fibre cell wall as a result of a reaction between the silanols and the hydroxyl group of the fibre (Agrawal et al., 2000). The reaction scheme is given as:

$$NH_2(CH_2)_3Si(OC_2H_5)_3 + 3H_2O \longrightarrow (HO)_3Si(CH_2)_3NH_2 + 3(C_2H_5OH).$$

2.5.4.3 Acetylation of Natural Fibres

Natural fibres are treated with acetic anhydride solution resulting in acetylation of hydroxyl groups. This causes swelling of plant fibre cells thereby reducing its water absorption capability. The treatment further eliminates waxes from the fibre causing better fibre-matrix bonding hence improved stress transfer efficiency at the interface resulting in better mechanical properties. Also, acetylated fibres have improved resistance to biological rotting, microbial attacks and ultraviolet radiation degradation. This treatment aims at reducing the hygroscopic attribute of natural fibres in addition to increasing composites dimensional stability (Rong et al., 2001). Acetylation of natural cellulosic fibres with acetic anhydride occurs as follows:

Cellulose fibre-OH + CH_3-CO-O-CO-CH_3 → Cellulosic fibre-O-CO-CH_3 + CH_3-CO-OH

2.5.5 Curing Cycle

In composite fabrication, curing cycle is controlled by three main processing parameters: temperature, pressure and time. The control of these parameters during the curing process helps to control water vaporization during cross-linking reaction. Curing at high temperature and pressure for a long period increases the rate of vaporization of water molecules resulting in voids formation hence reduced properties of the composites. To minimize the amount of voids formed during curing process, high final pressure should be applied to the composites only at the point of matrix cure consolidation (Jackson et al., 2009).

2.5.6 Effect of Moisture Absorption

The effect of moisture absorption on composites' mechanical properties has been analysed by Girisha et al., (2012). A comparative study was made between tensile and flexural strength of wetted and non-wetted sisal coir epoxy hybrid composites. Moisture absorption caused 9-14% reduction in flexural strength while tensile strength reduced by 3-16% due to the effect of moisture. In summary, natural fibre/polymer composites are hypersensitive to moisture. Moisture absorption causes a decrease in fibre/polymer composite properties and a loss of composites' functionality (Azwa et al., 2013).

2.6 Natural Fibre Composites

The use of natural fibres as reinforcement in composite fabrication has been reported in literature by various researchers. Sapuan et al., (2006) using hand lay-up fabrication technique produced banana fibre epoxy reinforced composites. The results obtained

showed that the composite exhibited maximum stress value of 14.14MN/m^2 and 3.398MN/m^2 in x-direction and y-direction respectively while the values for Young's modulus were 0.976 GN/m^2 and 0.863 GN/m^2 in x-direction and y-direction respectively. For flexural testing (three-point bending), a deflection of 3mm was recorded on application of 36.25 N load. The maximum stress and Young's modulus in x-direction was 26.181 MN/m^2 and 2.685 GN/m^2 respectively.

Maleque and Sapuan (2005) fabricated natural woven fabric reinforced epoxy composite for household telephone stand application. In their study, they deduced that banana fibre is a better reinforcement alternative for making stands since it is cheaper than synthetic fibres. Also, banana fibres can be used as a replacement for conventional metallic, non-metallic, plastic and wood materials.

Jawaid, Abdul and Abu (2011) investigated the tensile and flexural performance of tri-layer oil palm empty fruit bunches (EFB)/woven jute fibre reinforced epoxy hybrid composites produced using hand-layup. They observed that pure woven jute composite reported a high tensile strength of 53.31MPa as compared to 22.61MPa of pure EFB composite. This result was attributed to higher strength and stiffness of woven jute compared to EFB as well as excellent bonding between jute fibres in the fabric and epoxy matrix. They concluded that adding woven jute fibre in pure EFB composites improved the tensile and flexural properties of the resultant hybrid composites.

Gowda, Naidu and Chhaya (1999) studied the mechanical properties of jute fabric reinforced polyester composites. They observed that tensile and flexural properties increased with fabric reinforcement. However, there was a decrease in composite

hardness. This was attributed to hardness difference between jute fabric reinforcement and polyester resin. The impact properties were also found to improve considerably**.**

Low et al., (2009) investigated the mechanical properties of recycled cellulose fibre (RCF) reinforced epoxy composites. In their study, they found that reinforcement of epoxy matrix with RCF led to significant increase in strain at failure, impact toughness and fracture toughness. However, there was a moderate increase in flexural modulus and flexural strength. The impact strength was 1.3KJ/m^2 for RCF composites compared to 0.4KJ/m^2 for pure epoxy system.

Alamri and Low (2012) investigated the mechanical properties of recycled cellulose fibre (RCF) reinforced epoxy composites at 19, 28, 40 and 46 wt% fibre weight fraction. Results from the study indicated that fracture toughness, flexural modulus, flexural strength, and impact strength increased with fibre loading to attain maximum mechanical properties at 46 wt%.

Sastra et al., (2006) produced and determined the tensile properties of arenga pinnata fibre reinforced epoxy composites at 10%, 15% and 20% fibre weight fractions using hand lay-up manufacturing technique. They found that tensile properties increased with fibre loading to attain maximum tensile strength and Young's Modulus of 51.725MPa and 1.255GPa respectively at 20%V_{wf}.

Harish et al., (2006) evaluated the mechanical properties of coir reinforced epoxy composites using hand lay-up technique. The study showed an average tensile strength of 17.86±2.32MPa, flexural strength of 31.08±6.01MPa and impact strength of 11.49±0.99KJ/m^2.

Samson and Blanka (2015) used bark cloth natural nonwoven fabric and epoxy resin to fabricate Bark Cloth Laminar Epoxy Composites. The results showed that the flexural strength and tensile strength of the composite ranged from 45 to 100 MPa and 22 to 29 MPa respectively.

Vijay et al., (2010) synthesized and characterized novel ‘‘green’’ polymer composites from pine needles and a phenolic matrix by compression molding technique. They observed that the compressive strength increased with increase in fibre loading up to 30% fibre loading after which there was a decrease in compressive strength. Also, flexural properties of the resultant composites increased with fibre loading.

2.6.1 Sisal Fibre Reinforced Composites

Sisal fibre has been used as reinforcement with various matrices in composites fabrication for many applications as reported in literature. The fibre has been used both as loose fibres and woven fabric with thermosetting and thermoplastic polymers.

2.6.1.1 Sisal Fibre Reinforced Thermoset Composites

Bisanda and Ansell (1991) investigated the effect of silane and alkali treatment on the physical and mechanical properties of sisal epoxy composites. Their findings showed improved strength and stiffness as a result of incorporating the sisal fibres in epoxy resin. Also, fibre treatment using alkali solution followed by silane improved the water resistance, mechanical properties and wettability.

The influence of interfacial adhesion on fracture and mechanical behavior of short fibre reinforced thermoset (polyester, epoxy and phenol formaldehyde) and thermoplastic resin (Low density polyethylene, LDPE) in relation to fibre loading and fibre staple length has

been investigated by Joseph et al., (1996a). As they varied fibre loading, they observed that all composite properties improved with fibre loading.

Singh et al., (1996) investigated the effect of chemical treatment on the mechanical and physical properties of sisal fibre reinforced unsaturated polyester composite. They observed improved mechanical and physical properties of the composites as a factor of chemical modification. However, in humid conditions, the tensile and flexural strengths reduced by 30-44% and 50-70% respectively.

2.6.1.2 Sisal Fibre Reinforced Thermoplastic Composites

Weak interfacial bonding and poor wettability are the main challenges associated with natural fibre reinforced thermoplastic composites. They limit dimensional stability and contribute to low mechanical properties due to poor compatibility and dispersability between hydrophobic thermoplastics and hydrophilic cellulose fibres. In order to improve the fibre-matrix adhesion, natural fibres should be pre-treated or incorporate surface modifiers during processing of the composites (Carvalho, 1997).

Wambua et al., (2003) tested and compared the mechanical properties of various natural fibres (sisal, kenaf, coir, jute and hemp) reinforced composites. They further compared the mechanical properties of these composites with the corresponding glass mat reinforced polypropylene reinforced composites available from literature. The study showed that the specific properties of the natural fibre reinforced polypropylene composites were comparable with those of glass fibres. They also observed an increase in impact strength, tensile strength and ultimate tensile strength with increase in fibre weight fraction. Coir fibre reinforced composites showed the lowest mechanical properties except impact strength that was higher than that of jute and kenaf composites.

Joseph et al., (1996b) studied the effect of chemical treatment on tensile, electrical, dynamic, mechanical and ageing properties of short sisal fibre reinforced low density polyethylene (LDPE). They observed that chemical treatment improved the tensile properties of the composites and the degree of improvement varied from one chemical to another. The variation of composite tensile properties with different fibre treatment at fibre length 5.8mm and 30% fibre volume fraction is presented in Table 2.7.

Table 2.7: Tensile properties variation of longitudinally oriented LDPE-sisal composites (Joseph et al., 1996b)

Composites	Tensile Strength (MPa)	Elongation at Break (%)
Untreated	31.12	2
Alkali treated	34.27	1
Isocyanate treated	41.50	4
BP treated	40.90	3
DCP treated	41.80	4
KMnO4 treated	38.80	3

Oladele et al., (2013) investigated the effect of chemical modification of fibres on mechanical properties of sisal reinforced polypropylene (PP) composites using the compression molding technique. The fibres were chemically treated with 1M potassium hydroxide, hydrogen chloride, ethanol and sodium chloride respectively while other fibres were not treated, representing the control samples. The study findings showed that chemical treatment enhanced the mechanical properties of the fibres and resultant composites.

Joseph et al., (1992, 1993a,b & 1994) investigated the viscoelastic, mechanical, electrical and rheological properties of short sisal fibre reinforced with low density polyethylene (LDPE) composites using fibre orientation, fibre length, fibre content and processing

method as design variables. They observed that fibre length, fibre dispersion, fibre loading, fibre-matrix interfacial bond strength and fibre orientation influence the tensile strength and modulus of the resultant composites.

Joseph et al., (1999) analyzed the tensile properties of solution mixed sisal fibre reinforced polypropylene (PP), polystyrene (PS) and low density polyethylene (LDPE). They found that the tensile strength and modulus of both sisal/PP and sisal/LDPE increased with fibre content. On the other hand, sisal/PS composites showed 40% decrease in tensile strength with 10% fibre loading. However, sisal-PP composite showed 3% increase in tensile strength at 10%V_{wf}. They further deduced that the tensile strength of sisal/PP and sisal/PS are comparable at high fibre loading.

2.6.1.3 Sisal Fibre Reinforced Rubber Composites

In a study to evaluate the moisture sorption characteristic and tensile properties of woven sisal fabric reinforced natural rubber biocomposites, Maya et al., (2006) subjected unidirectional sisal fabric to silanization and alkali treatment using NaOH solution of 4% concentration for 1 hour and thermal treatment in an oven at 150^0C for 8 hours. The study indicated that moisture sorption of the textile biocomposites was dependent on fibre content and architecture. Also, the treated composites recorded higher tensile strength compared to untreated composites.

2.7 Research Gap

Limited to the above literature review, sisal reinforced polymer composites have been majorly fabricated using sisal in “fibre form”. The current study aims at using sisal fibre in “fabric form”. Woven fabric reinforcement is characterized by unidirectional orientation of fibres in the fabric hence minimal or no fibre orientation. This reduces

agglomerations and fibre pull outs resulting into maximum stress transfer from matrix to the fibres. Hence, the fibres can withstand high mechanical strengths before failure resulting into higher mechanical properties of resultant composites. Factors such as fabric geometry, weave type and fibre weight fraction affect the mechanical properties of woven fabric reinforced composites. According to Kim and Sham (2000), textile biocomposites can be designed by altering the weave and fabric geometry to obtain the required specific needs of mechanical performance of composite materials. Based on this research gap, the current work intends to fabricate and determine the tensile, compressive, impact and flexural properties of woven sisal fabric reinforced epoxy composites and make contribution to the existing literature on sisal fibre reinforced polymer composites.

CHAPTER THREE: MATERIALS AND METHODOLOGY

3.1 Introduction

This chapter gives the procedures and materials used in fabricating woven sisal fabric reinforced epoxy composites, mechanical testing and analysis of the results. Composite fabrication was carried out in the Mechanical laboratory, School of Engineering, Moi University, while mechanical tests were performed in the Technical University of Kenya and Rivatex East Africa Limited laboratories.

3.2 Materials

3.2.1 Woven Sisal Fabric

Woven sisal fabric used as reinforcement was sourced from Premier Bags and Cordage industry, Juja-Kenya. The plain woven sisal fabric (see Fig. 3.1) was characterized to determine its properties. In order to determine the effect of alkali treatment on the mechanical properties of the composites, some sisal fabrics were subjected to 4% w/v alkali treatment for one hour and pre-dried in an oven at 80^0C for another one hour. In most cases, sisal fibres are pre-coated with commercially available surface coating such as starch and lubricants to enhance weaving process. However, the effect of these coatings (if any) was ignored in this research.

Figure 3.1: Sisal woven fabric

3.2.2 Epoxy Resin and Hardener (Matrix)

Epoxy resin Lapox B-47 of density 1.06–1.18 g/cm^3, mixed with hardener ARADUR 3486 of density 0.92–0.98 g/cm^3 were used in the preparation of the composites. Both the resin and hardener were purchased from *Araldie City Suppliers*, Nairobi. The epoxy resin and hardener were mixed in the ratio of 5:3 by weight as per manufacturer's instructions. The viscosity of the resin was 25-40 poise at 25^{0}C. Other properties of the resin are as indicated on Table 3.1.

Table 3.1: Properties of the epoxy resin

Technical Name	Araldite Laminating Resin
Density	1.06-1.18 g/cm^3
Curing Conditions	Room temperature (24h); or 40ºC (4-6h); or 65ºC (45-60min); or 100ºC (15min)
Tensile Strength	85MPa
Modulus of Elasticity, E	10,500MPa
Elongation at break	0.8%

3.2.3 Mould Release Agent and Gel Coat

Mould release agent (MRA) and white gel coat were sourced from Specialized Fibreglas Ltd, Nairobi. The mould release agent was used in composite fabrication to prevent sticking of the resultant composite on the mould. The gel coat was used to improve the surface texture of the composites. However, the effect of the gel coat on the mechanical properties of the composites was not investigated. It was assumed the effect, if any, was minimal.

Figure 3.2: Mould release agent (MRA) and gel Coat

3.2.4 Sodium Hydroxide

Sodium hydroxide (NaOH) pellets were purchased from Yokhama Enterprises, Eldoret. These were used for alkali treatment of cellulosic sisal fibres to enhance interfacial bonding between the fibres and matrix in the composites.

3.2.5 Aluminium Foil

A thin plastic velvex aluminium foil was obtained from a supermarket in Eldoret. It was used to ensure good surface finish of the resultant composites.

3.3 Methodology

3.3.1 Characterization of the Sisal Fabrics

Prior to the fabrication of the composites, the sisal fabric was characterized to determine its properties. This involved determining the properties of the yarns (forming the fabric) and the woven fabric.

3.3.1.1 Yarn

Warp and weft yarns were carefully removed from the woven sisal fabric. The yarn properties were determined as follows:

(a) Count

The weft and warp yarn count was measured in accordance with BS 947:1970 standards using weighing machine Model ADAM PGW 453e (see Fig. 3.3). The length of each weft and warp yarn was also measured using one-meter ruler. The count of each yarn was determined from weight and length measurements.

Figure 3.3: Electronic weighing machine

(b) Tensile Strength

The tensile strengths of both warp and weft yarn was measured according to ASTM 2256 standards using Universal Testing Machine (type TH2730; S/N: 04-774-2008) (see Fig.

3.4) at 200 mm machine gauge length and 100 mm/min cross head speed. The specimens were loaded unto the machine and tightly clamped. The machine was run to the point of yarn breakage. The machine recorded both the maximum force at the point of yarn breakage and breaking extension. For each weft and warp yarn, ten samples were tested.

Figure 3.4: Universal testing machine

Yarn tensile strength in terms of breaking tenacity was calculated using Eq. 3.1, as follows:

$$\text{Breaking tenacity (cN/Tex)} = \frac{\text{Breaking force (cN)}}{\text{Linear density (Tex)}} \qquad (3.1)$$

3.3.1.2 Fabric

(a) Fabric Weight

The weight of the fabric was determined in accordance with ASTM D 3776–96. The fabric was cut into five samples each measuring 72 cm (full width) by 30 cm using a pair of scissors. The weight was measured using an electronic balance (see Fig. 3.3). The weight of each sample was measured thrice and the average weight recorded.

(b) Tensile Strength and Modulus

The tensile property of woven sisal fabric was measured according to ASTM 5034-95 standards using Universal Testing Machine (see Fig. 3.4). The samples were cut (avoiding the helms/edges of the fabric) using a pair of scissors into rectangular shape measuring 250 mm by 50 mm. The machine settings were gauge length 200 mm and machine cross-head speed 100 mm/min. The fabric tensile strength was determined in warp (or machine) direction and the weft (or cross) direction. Ten samples were tested in each direction.

The fabric tensile strength was calculated by;

$$\text{Tensile strength} = \frac{\text{Maximum load}}{\text{Original area}} \qquad (3.2)$$

The Modulus of Elasticity (E) of the fabric was obtained from the initial linear portion of stress-strain curve. The value of E was obtained by dividing the difference in stress corresponding to any segment of section of this straight line by the corresponding difference in strain.

3.3.2 Fabric Modification

3.3.2.1 Alkali Treatment

The sisal fabric was subjected to alkali treatment at 4% w/v NaOH for one hour and then rinsed thoroughly in distilled water until it was alkali free (observed using litmus paper). Alkali treatment served to improve the dispersion of the fibre in the matrix and reduce agglomeration by minimizing hydrogen bonding responsible for holding them together. The washed fabric was pre-dried in an oven.

3.3.2.2 Oven Pre-drying

The sisal fabric was kept in an oven for 1 hour at 80^0C, removed and used for composites fabrication. Oven pre-drying served to remove excess moisture from the fabric thus improving the degree of bonding between the fabric and epoxy resin thereby increasing interfacial adhesion.

3.3.3 Mould Preparation

A mould measuring 310 x 310 x 10 mm and a lid measuring 300 x 300 mm with sufficient stiffness to withstand handling loads was fabricated in the School of Engineering Workshop using stainless steel sheet. The purpose of the lid was to provide a uniform surface and cover the fibres after application of epoxy matrix and to avoid debris and other impurities from entering into the composite parts during the curing process.

Figure 3.5: A mould measuring 310 x 310 x 10 mm

3.4 Experimental Design

Experiments with two dependent design variables namely fibre weight fraction (X_1) and number of fabric layers (X_2) were conducted using full factorial Central Composite

Rotatable Design (CCRD) experimental design with two levels coded by -1.4142, -1, 0, +1 and +1.4142. α was determined using Eq. 3.3, as follows:

$$\alpha = (2^k)^{1/4} \qquad (3.3)$$

Where k=2. This gives the values of α as:

$$\alpha = (2^2)^{1/4} = 1.4142$$

Table 3.2: Physical and coded values of composite parameters for design of experiments

Parameter/levels	Lowest	Low	Centre	High	Highest
Coded-classical experimental design	-1.4142	-1	0	+1	+1.4142
Fibre weight fraction (wt%), x_1	30	40	45	50	60
Number of fabric layers (n_o), x_2	1	2	2 or 3	3	4

The total number of experiments, N using MATLAB software is given as;

$$N = 2^k + 2k + n_o \qquad (3.4)$$

The design of experiment comprised of a complete 2^2–factorial design (run 1-4), n_o center points/replicates (n_o>1) (run 5-8) and two axial points (run 9-12) on the axis of each design variable (known as star points) at a distance of α=1.4142 from the design center. The center point was replicated 4 times (n_o =4) to give three degrees of freedom for error calculation in the experiments. A total of twenty-four fabrications with different variations were carried out, 12 each for treated and untreated fabrics respectively (see Table 3.3).

Table 3.3: Parameter levels of CCRD (coded value) for response variable

Test number	Coded Factors		Response Variable Y_s	
	X_1	X_2	Treated sample	Untreated sample
1	-1	-1		
2	-1	1		
3	1	-1		
4	1	1		
5	0	0		
6	0	0		
7	0	0		
8	0	0		
9	-1.4142	0		
10	1.4142	0		
11	0	-1.4142		
12	0	1.4142		

3.5 Composite Fabrication

Composite samples were produced using the hand lay-up fabrication technique. This is the simplest method with minimum capital and infrastructural requirement.

Untreated composites were first prepared using untreated fibres. Similarly, alkali treated composites were fabricated using treated fibres in order to investigate the effect of alkali (NaOH) treatment of cellulosic sisal fibres on the mechanical properties. Both the control and alkali treated sisal fabric composites were prepared in the same way.

The following experimental procedure was followed in fabrication of treated and untreated composites.

a) The mould was cleaned thoroughly and dried.

b) The weight of the reinforcement was measured with an electronic balance taking into account the number of layers for each experimental set-up/run. From the weight of the reinforcement and the corresponding fibre weight fraction, the weight of the matrix (resin/hardener) was determined. The individual weights of

the resin and hardener were obtained from the recommended manufacturer's mixing ratio of 5:3. The resin and hardener mixture was thoroughly stirred with a rod for 5 minutes to ensure uniform mixing before applying on the reinforcement.

c) Mould release agent followed by a gel coat was applied on the mould surface. A thin plastic velvex aluminium foil was then placed on the mould.

d) Woven sisal fabric reinforcement was then placed on then aluminium foil.

e) Epoxy matrix was uniformly applied with a brush and squeezed in with a pressure roller (Fig. 3.6) to ensure uniform impregnation of the fabric with matrix.

Figure 3.6: Application and squeezing the matrix into the fibres

f) Another layer of woven fabric was added and pressed against the first layer of the fabric with a roller to get rid of any excess matrix and trapped air. Trapped air could lead to blistering in case the molding is exposed to heat or water during its working life. Steps (e) & (f) were repeated until the required fabric layers and fibre weight fraction was achieved.

g) A plastic Perspex sheet was placed on the inner surface of the top mould plate followed by spraying of release agent to avoid sticking of the sheet on mould plate (Fig. 3.7).

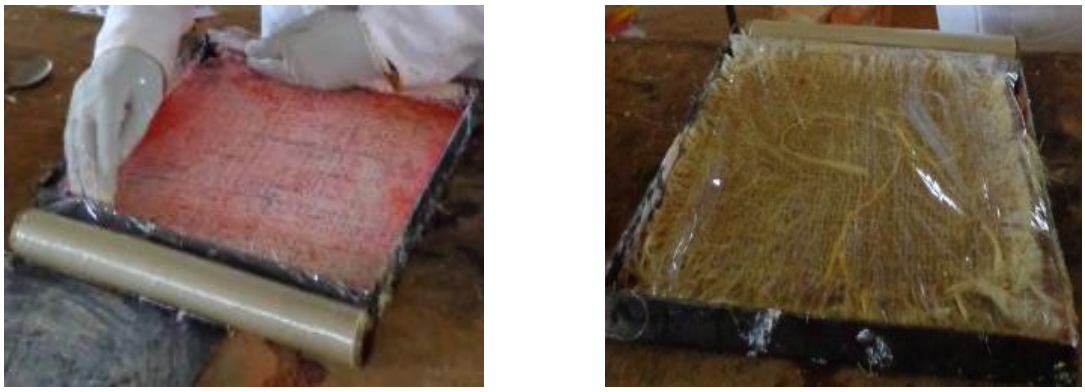

Figure 3.7: Wrapping of Aluminum foil to the bottom and top of the mould

h) The mould was closed with a metallic lid and bricks of mass 30 kg placed on top of the mould. This generated a pressure of 3.3 KN/m^2 to ensure uniform consolidation of the materials and hence minimize the number of voids in the composite.

i) The composite was allowed to cure for 24 hours at room temperature. The mould was opened to remove the composite.

j) The procedure (a) – (i) was then repeated as required.

3.6 Mechanical Testing

The composite samples were cut as per the ASTM Standards and conditioned in the textile laboratory at Rivatex for 48 hours at ambient conditions of temperatures (23 ± 2^0C) and relative humidity (65%) before performing any test.

3.6.1 Tensile Test

Tensile tests were conducted as per ASTM D638 using Universal Testing Machine (type TH2730; S/N: 04-774-2008) with crosshead speed of 2 mm per minute and a load cell of 5KN.

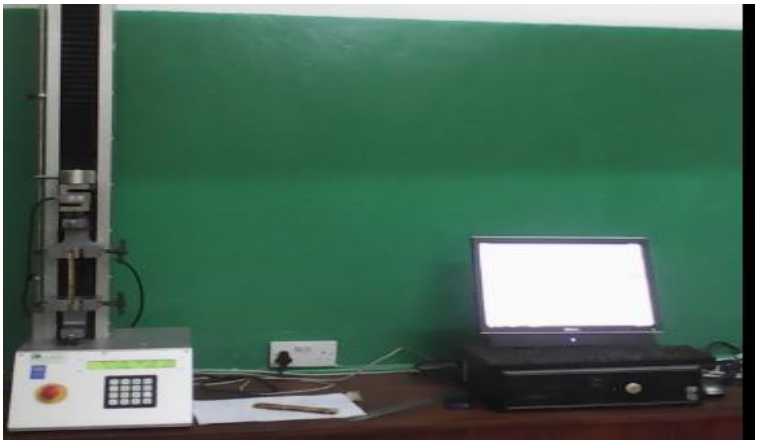

Figure 3.8: Universal materials testing machine

For each treated and untreated sample, ten specimens were tested. The tests were performed to the point of specimen yield and the corresponding average maximum tensile loads before failure reported. The tensile strengths of the composites were calculated by dividing the maximum load by the original minimum cross sectional area of the specimens as given by Eq. 3.5.

$$\text{Tensile strength} = \frac{\text{Maximum load}}{\text{Original cross sectional area}} \qquad (3.5)$$

The Modulus of Elasticity (E) of woven sisal reinforced epoxy composites was determined from the initial linear portion of the stress-strain curve. It was obtained by dividing the difference in stress corresponding to any segment of section of this straight line by the corresponding difference in strain.

3.6.2 Compression Test

Compression tests were carried out on a Universal materials testing machine (see Fig. 3.8) in accordance with ASTM D3410 Standard at a crosshead speed of 5 mm per minute and a load of 5KN. For each treated and untreated sample, ten specimens were tested and the average maximum compressive load carried by the specimens reported. The

compressive strength of the composites were calculated by dividing the maximum compressive load carried by the specimen during tests by the original minimum cross sectional area of the specimens as given by equation 3.6.

$$\sigma_{FC} = \frac{\rho_{\max}}{A} \qquad (3.6)$$

where σ_{FC} is compressive strength (MPa), $\rho_{\max}$ is the maximum compressive load (N), and A is the cross-sectional area (mm^2).

The compressive modulus of woven sisal reinforced epoxy composites was determined from the initial linear portion of the compressive strength-strain curve by dividing the difference in compressive strength by the corresponding difference in strain.

3.6.3 Impact Tests

Impact tests were conducted on a Charpy impact tester model JB-300w (serial number W1303) with maximum impact energy of 300J (see Fig 3.9). This research adopted a test method that was consistent to ISO 179-1:2000. Impact loading was done with a 15 J-hammer.

Figure 3.9: Charpy impact tester

All the test specimens were un-notched. A total of ten specimens for each sample of treated and untreated sisal reinforced epoxy composites were tested and the average value

of the absorbed energy to break these specimens was used to calculate composites' impact strength using Eq. 3.7, as follows:

$$a_{cU} = \frac{E}{h.b} * 10^3 \qquad (3.7)$$

Where a_{cU} is the Charpy impact strength of un-notched specimens (KJ/m^2), h is the thickness (mm), b is the width (mm) and E is the energy absorbed (J) by breaking the test specimens

3.6.4 Flexural Tests

The flexural (three–point bending) test was carried out in accordance with ASTM D790 on a computer controlled Universal Materials Testing Machine with a load cell of 5KN at a crosshead speed of 2mm per minute. The distance between the supports (span length), width and overall length of the specimens were varied based on variations on sample thickness as per standard procedures as:

Span length (L): 16 times specimen thickness (to the nearest whole number)

Specimen width (b): $\frac{1}{4}$ times span length (to the nearest whole number)

Overall length: 25mm overhanging allowance on both sides + individual span length

For each composite specimen, ten specimens were tested until failure occurred in the outer surface and the average recorded. The flexural strength of the composites was calculated using Eq. 3.8, as follows:

$$\text{Flexural strength } \sigma_f = \frac{3F_{max}.L}{2bh^2} \qquad (3.8)$$

Where F_{max} is maximum load (N), L is span length (mm), h is thickness (mm), b is width (mm) and σ_f is flexural strength (MPa)

The flexural modulus of woven sisal reinforced epoxy composites was determined from the initial linear portion of the flexural strength-strain curve. It was obtained by dividing the difference in flexural strength by the corresponding difference in strain.

There were slight variations in the mechanical properties of the composites within the same fibre weight fraction. To analyze the effect of fibre weight fraction on mechanical properties of the untreated composites, the study used the value with higher mechanical property within the same fibre weight fraction.

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Weights of Reinforcement, Resin and Hardener

Table 4.1(a) and table 4.1(b) show the weights of reinforcements, resin and hardener used in the fabrication of untreated and treated sisal reinforced epoxy composites respectively. From the results, it is clear that for the same fibre weight fraction, the total weights are different for treated and untreated fibres. Alkali treated fibres showed higher fibre weight due to the moisture absorbed during rinsing that was not fully removed during oven pre-drying.

Table 4.1(a): Weights of reinforcement and matrix for untreated fibres

Run	Number of layers	Total weight of layers (g)	V_{wf} (%)	Matrix weight (g)	Resin weight (g)	Hardener weight (g)
1	2	113.83	40	170.75	106.72	64.03
2	3	172.90	40	259.35	162.09	97.26
3	2	114.97	50	114.97	71.86	43.11
4	3	173.04	50	173.04	108.15	64.89
5	2	115.61	45	141.30	88.31	52.99
6	3	172.68	45	211.05	131.91	79.15
7	2	113.94	45	139.26	87.04	52.22
8	3	170.32	45	208.17	130.11	78.06
9	2	114.45	30	267.05	166.91	100.14
10	3	172.09	60	114.73	71.70	43.02
11	1	57.08	45	69.76	43.60	26.16
12	4	229.23	45	280.17	175.11	105.06

Table 4.1(b): Weights of reinforcement and matrix for treated fibres

Run	Number of layers	Total weight of layers (g)	V_{wf} (%)	Matrix weight (g)	Resin weight (g)	Hardener weight (g)
1	2	122.43	40	183.65	114.78	68.87
2	3	192.62	40	288.93	180.58	108.35
3	2	125.56	50	125.56	78.48	47.09
4	3	195.43	50	195.43	122.14	73.29
5	2	120.32	45	147.06	91.91	55.15
6	3	193.01	45	235.90	147.44	88.46
7	2	119.92	45	146.57	91.61	54.96
8	3	196.09	45	239.67	149.79	89.87
9	2	121.29	30	283.01	176.88	106.13
10	3	195.72	60	130.48	81.55	48.93
11	1	62.48	45	76.36	47.73	28.64
12	4	240.92	45	294.46	184.04	110.42

4.2 Properties of Woven Sisal Reinforcement

4.2.1 Yarn

4.2.1.1 Yarn Count

Table 4.2(a) and table 4.2(b) show the measured warp and weft yarn count. During measurement of weft and warp yarn count, high weight variation of sisal yarn was observed. This can be attributed to inconsistent spinning process along the entire length of the yarn resulting into thick and thin areas. These variations affect the quality of the final fabric. This can be corrected through machine setting and close monitoring of the spinning process.

Table 4.2 (a): Warp yarn count

S/No	Weight (g)	Length (cm)	Count (Tex)
1	1.24	38.50	3220.78
2	1.04	38.50	2688.31
3	0.37	35.00	1052.38
4	0.52	37.50	1384.00
5	0.46	38.00	1208.77
6	0.49	37.20	1312.72
7	0.86	37.30	2288.65
8	0.48	37.60	1271.28
9	0.57	37.50	1526.22
10	0.53	37.00	1431.53
		Mean	1738.65

Table 4.2 (b): Weft yarn count

S/No	Weight (g)	Length (cm)	Count (Tex)
1	0.55	35.00	1582.86
2	0.73	35.00	2095.24
3	0.76	36.00	2099.07
4	0.21	34.00	629.41
5	0.49	35.00	1411.43
6	0.27	34.50	795.17
7	0.34	34.50	984.54
8	0.35	34.00	1014.71
9	0.47	35.00	1340.96
10	0.58	34.00	1705.88
		Mean	1365.93

4.2.1.2 Yarn Tensile Strength

The tensile properties of the warp and weft yarns are presented in Table 4.3(a) and Table 4.3(b). From the results, it can be deduced that warp yarn can withstand more loads (2058.28cN) under tension when compared to weft yarn (1579.80cN) before breaking. Also, warp yarn tenacity is higher (1.43cN/Tex) than that of weft yarn (1.31cN/Tex). The higher tensile properties (strength and tenacity) of warp yarn can be explained by higher count (1738.65Tex) compared to weft yarn count (1365.92Tex) reported in this study. The elongation at break of warp yarn (2.80%) was also higher than that of weft yarn (2.43%). The higher tensile properties of warp yarn can be attributed to sizing chemicals such as starch mainly applied on warp yarn to improve their performance since the warp yarns are subjected to mechanical abrasion during weaving. The tensile properties of the yarn affect the tensile strength of the fabrics made from the yarn. For instance, yarn tensile strength in addition to other factors such as fabric construction and manufacturing operations influence the breaking strength of the fabric (Bledzki et al., 1996).

Table 4.3(a): Warp yarn tensile properties

Sample	Maximum load, cN	Breaking extension, mm	Elongation at break , %	Count (Tex)	Breaking tenacity, cN/Tex
1	2442.08	10.36	2.69	3220.78	0.76
2	1150.58	7.63	1.98	2688.31	0.43
3	2386.64	10.11	2.89	1052.38	2.27
4	2671.69	13.22	3.52	1384.00	1.93
5	1258.57	6.19	1.63	1208.78	1.04
6	1804.64	7.67	2.06	1312.72	1.37
7	3781.62	9.20	2.47	2288.65	1.65
8	1950.97	16.63	4.42	1271.28	1.53
9	2138.23	14.63	3.90	1526.22	1.40
10	997.76	8.93	2.41	1431.53	0.70
Mean	2058.27	10.93	2.93	1738.65	1.43

Table 4.3(b): Weft yarn tensile properties

Sample	Maximum load, cN	Breaking extension, mm	Elongation at break , %	Count, Tex	Breaking tenacity, cN/Tex
1	1900.61	7.87	2.25	1582.86	1.20
2	1550.76	8.80	2.51	2095.24	0.74
3	898.07	5.55	1.54	2099.07	0.43
4	2823.21	9.09	2.67	629.41	4.49
5	1520.85	7.43	2.12	1411.43	1.08
6	894.65	6.41	1.86	795.17	1.13
7	2141.16	11.79	3.42	984.54	2.17
8	1295.45	9.05	2.66	1014.71	1.28
9	865.60	7.59	2.17	1340.95	0.65
10	1907.64	10.51	3.09	1705.88	1.12
Mean	1579.80	8.41	2.43	1365.93	1.31

4.2.2 Woven Fabric

4.2.2.1 Weight

Table 4.4 shows the measured fabric weights. There were variations in fabric weight as result of variations in warp and weft yarn weight as explained above.

Table 4.4: Fabric weight (g)

No.	Weight 1	Weight 2	Weight 3	Mean weight
1	149.27	149.15	149.32	149.25
2	151.58	151.65	151.65	151.63
3	183.94	183.92	183.92	183.93
4	164.73	164.76	164.78	164.76
5	160.80	160.73	160.78	160.77

4.2.2.2 Tensile Properties

The tensile properties of the woven fabric were tested in both warp and weft direction and the results presented in Table 4.5(a) and Table 4.5(b). From the results, it can be shown that woven fabric can sustain higher tensile loads when loaded along the warp direction than in the weft direction. Also, breaking extension and elongation at break, was lower when woven fabrics were tested along the weft direction compared to testing along the warp direction. This phenomenon can be explained by higher tensile properties of warp yarns compared to weft yarns.

Table 4.5 (a): Tensile properties of woven sisal fabric along warp direction

Sample	Maximum load, N	Breaking extension, mm	Elongation at Break, %	Tensile strength, MPa	Tensile modulus, MPa
1	806.82	19.06	9.53	8.07	846.83
2	804.64	16.94	8.47	8.05	950.16
3	832.47	19.90	9.95	8.33	836.56
4	933.83	18.05	9.03	9.34	1034.72
5	323.76	11.52	5.76	3.24	562.28
6	911.28	20.07	10.04	9.11	908.01
7	741.57	19.65	9.82	7.42	754.81
8	964.61	25.52	12.76	9.65	756.11
9	609.14	17.06	8.53	6.09	714.11
10	263.62	12.20	6.10	2.64	432.17
Mean	719.17	18.00	9.00	7.19	799.28

Table 4.5 (b): Tensile properties of woven sisal fabric along weft direction

Sample	Maximum load, N	Breaking extension, mm	Elongation at Break, %	Tensile strength, MPa	Tensile modulus, MPa
1	433.25	16.90	8.45	4.33	512.63
2	409.59	12.56	6.28	4.10	652.22
3	472.30	10.67	5.34	4.72	884.95
4	771.48	12.17	6.09	7.72	1267.41
5	613.81	12.70	6.35	6.14	966.70
6	659.53	12.31	6.16	6.60	1071.54
7	496.67	13.76	6.88	4.97	722.06
8	787.40	11.00	5.50	7.87	1431.89
9	790.47	13.58	6.79	7.91	1164.34
10	572.08	15.17	7.59	5.72	754.08
Mean	600.66	13.08	6.54	6.01	918.25

4.3 Mechanical Properties

The results of the measured mechanical properties of the woven sisal fabric reinforced epoxy composites are presented below.

4.3.1 Tensile Properties of Sisal Composites

(a) Tensile Strength

Specimen length: 165 mm

Specimen width: 19 mm

Gauge length: 115 mm

Table 4.6(a): Tensile properties of the untreated composites

Specimen No.	Thickness, mm	Cross-sectional area, mm^2	Maximum load, N	Tensile strength, MPa	Tensile modulus, GPa
1	5.17	98.23	2628.67	26.76	2.95
2	7.33	139.27	3371.14	24.21	1.97
3	5.23	99.37	3151.48	31.72	4.70
4	7.27	138.13	4268.98	30.91	3.73
5	5.30	100.70	2831.37	28.12	3.28
6	7.67	145.73	3834.55	26.31	2.53
7	5.33	101.27	2858.75	28.23	3.30
8	7.63	144.97	3815.51	26.32	2.60
9	5.03	95.57	2162.70	22.63	2.15
10	7.60	144.40	3429.20	23.75	4.26
11	2.43	46.17	762.67	16.52	2.30
12	9.53	181.07	3291.49	18.18	2.10

Table 4.6(b): Tensile properties of the alkali treated composites

Specimen No.	Thickness, mm	Cross-sectional area, mm^2	Maximum load, N	Tensile Strength, MPa	Tensile modulus, GPa
1	4.20	79.80	2403.94	30.13	3.87
2	6.37	121.03	3485.19	28.90	2.37
3	4.33	82.27	3175.70	38.60	5.29
4	6.53	124.07	4334.66	34.94	4.48
5	4.30	81.70	2678.84	32.79	4.14
6	6.60	125.40	4006.07	31.95	3.14
7	4.33	82.27	2694.45	32.75	4.12
8	6.63	125.97	4021.72	31.93	3.14
9	4.47	84.93	2436.49	28.69	2.95
10	6.70	127.30	3667.25	28.81	5.03
11	2.23	42.37	835.11	19.71	2.74
12	7.97	151.43	3213.46	21.22	2.60

For all the composites tested, tensile strength increased as a result of chemical treatment of the fibres. For instance, the tested composites showed maximum tensile strength of 38.60 MPa for treated compared to 31.72 MPa for untreated composites. The higher tensile strength of treated compared to untreated composites can be attributed to excellent interface between the fibres and matrix due to lignin removal and fibre surface modification as a result of alkali treatment. Treatment of fibres with NaOH removes cementing materials such as lignin and hemicellulose present in the fibre hence increasing the fibre surface area. An increase in fibre surface area enhances better adhesion between the fibre and matrix resulting in improved tensile strength. On the other hand, the removal of these cementing materials present in the fibres tends to increase the

crystallinity of treated fibres resulting in better packaging of cellulose chains. Secondly, alkali treatment enhances mechanical interlocking between individual fibres causing improved fibre surface roughness and an increase in the number of possible reaction sites (Girisha et al., 2012).

4.3.2 Impact Strength

Specimen length: 80 mm

Width: 10 mm

Span length: 62 mm

Table 4.7(a): Impact strengths of the untreated composites

Specimen No.	Thickness (mm)	Cross-sectional area, mm^2	Absorbed energy, J	Impact strength, KJ/m^2
1	5.17	51.70	1.10	21.28
2	7.33	73.30	1.50	20.46
3	5.23	52.30	1.19	22.75
4	7.27	72.70	1.55	21.32
5	5.30	53.00	1.30	24.53
6	7.67	76.70	1.80	23.47
7	5.33	53.30	1.31	24.58
8	7.63	76.30	1.80	23.59
9	5.03	50.30	0.90	17.89
10	7.60	76.00	1.40	18.42
11	2.43	24.30	0.33	13.58
12	9.53	95.30	1.10	11.54

Table 4.7(b): Impact strengths of the alkali treated composites

Specimen No.	Thickness (mm)	Cross-sectional area, mm^2	Absorbed energy, J	Impact strength, KJ/m^2
1	4.20	42.00	1.15	27.38
2	6.37	63.70	1.70	26.69
3	4.33	43.30	1.22	28.18
4	6.53	65.30	1.71	26.19
5	4.30	43.00	1.40	32.56
6	6.60	66.00	2.00	30.30
7	4.33	43.30	1.42	32.79
8	6.63	66.30	2.02	30.47
9	4.47	44.70	1.10	24.61
10	6.70	67.00	1.52	22.69
11	2.23	22.30	0.41	18.39
12	7.97	79.70	1.14	14.30

The woven sisal reinforced epoxy composites tested showed fairly high impact strengths with maximum values of 32.79 KJ/m^2 and 24.58 KJ/m^2 for treated and untreated composites respectively and minimum values of 14.30 KJ/m^2 and 11.54 KJ/m^2 for treated and untreated composites respectively.

4.3.3 Compressive Strength

Specimen overall length: 85 mm

Specimen width: 25 mm

Gauge length: 25 mm

Table 4.8(a): Compressive properties of the untreated composites

Specimen No.	Thickness, mm	Cross-sectional area, mm^2	Compressive load, N	Compressive Strength, MPa	Compressive modulus, GPa
1	5.17	129.25	2329.83	18.03	2.03
2	7.33	183.25	3097.33	16.90	1.65
3	5.23	130.75	3007.69	23.00	2.32
4	7.27	181.75	4148.92	22.83	2.51
5	5.30	132.50	2655.97	20.05	2.41
6	7.67	191.75	4047.21	21.11	1.98
7	5.33	133.25	2691.62	20.20	2.36
8	7.63	190.75	4061.06	21.29	1.96
9	5.03	125.75	1925.88	15.32	1.92
10	7.60	190.00	4548.78	23.94	2.90
11	2.43	60.75	797.48	13.13	1.86
12	9.53	238.25	3369.96	14.15	1.79

Table 4.8(b): Compressive properties of the alkali treated composites

Specimen No.	Thickness, mm	Cross-sectional area, mm^2	Compressive load, N	Compressive Strength, MPa	Compressive modulus, GPa
1	4.20	105.00	2337.40	22.26	2.74
2	6.37	159.25	3348.88	21.03	1.90
3	4.33	108.25	3063.80	28.30	2.97
4	6.53	163.25	4406.22	26.99	2.95
5	4.30	107.50	2679.33	24.92	2.86
6	6.60	165.00	4135.03	25.06	2.69
7	4.33	108.25	2677.29	24.73	2.91
8	6.63	165.75	4168.09	25.15	2.65
9	4.47	111.75	2191.82	19.61	2.24
10	6.70	167.50	4665.51	27.85	3.10
11	2.23	55.75	912.80	16.37	2.03
12	7.97	199.25	3772.70	18.94	2.05

The compressive strengths of the composites ranged from a minimum of 16.37 MPa (treated) and 13.13 MPa (untreated) to a maximum of 28.30 MPa and 23.94 MPa for alkali treated and untreated composites respectively. This indicates that treating the woven sisal fabric increased the compressive strength of the composites. Alkali treatment enhances fibre-matrix adhesion as a result of removal of hemicellulose and lignin thus increasing the fibre surface area and hence resulting in higher compressive strength for treated composites compared to the untreated composites.

4.3.4 Flexural Strength

Table 4.9(a): Flexural properties of the untreated composites

Specimen No.	Thickness (h) mm	Span Length (L) mm	Width (b) mm	Max. Load, N	Flexural Strength, MPa	Flexural modulus, GPa
1	5.17	83.00	21.00	98.96	21.95	2.27
2	7.33	118.00	30.00	201.26	22.10	1.85
3	5.23	84.00	21.00	119.30	26.17	2.83
4	7.27	117.00	30.00	226.05	25.02	2.79
5	5.30	85.00	22.00	110.61	22.82	2.65
6	7.67	123.00	31.00	236.34	23.91	2.12
7	5.33	86.00	22.00	109.74	22.65	2.64
8	7.63	123.00	31.00	233.49	23.87	2.11
9	5.03	81.00	21.00	83.83	19.17	2.09
10	7.60	122.00	31.00	265.75	27.16	3.06
11	2.43	39.00	10.00	14.59	14.45	2.08
12	9.53	153.00	39.00	271.32	17.58	1.98

Table 4.9(b): Flexural properties of the alkali treated composites

Specimen No.	Thickness, (h) mm	Span Length (L) mm	width (b) mm	Max. Load, N	Flexural Strength, MPa	Flexural modulus, GPa
1	4.20	68.00	17.00	70.32	23.92	2.98
2	6.37	102.00	26.00	169.70	24.61	2.09
3	4.33	70.00	18.00	93.63	29.13	3.51
4	6.53	105.00	27.00	209.65	28.68	3.42
5	4.30	69.00	18.00	86.24	26.82	3.18
6	6.60	106.00	27.00	200.46	27.10	2.81
7	4.33	70.00	18.00	86.59	26.94	3.15
8	6.63	107.00	27.00	201.13	27.20	2.83
9	4.47	72.00	18.00	73.36	22.03	2.49
10	6.70	108.00	27.00	217.04	29.01	3.73
11	2.23	36.00	9.00	15.57	18.78	2.34
12	7.97	128.00	32.00	215.02	20.31	2.11

4.4 Effect of Alkali Treatment on the Mechanical Properties of the Composites

a) Effect of alkali treatment on tensile, flexural and compressive strengths of the composites at 40wt.%

Fig. 4.1 shows the results of alkali treatment on the tensile, flexural and compressive strengths of the composites at 40wt.%.

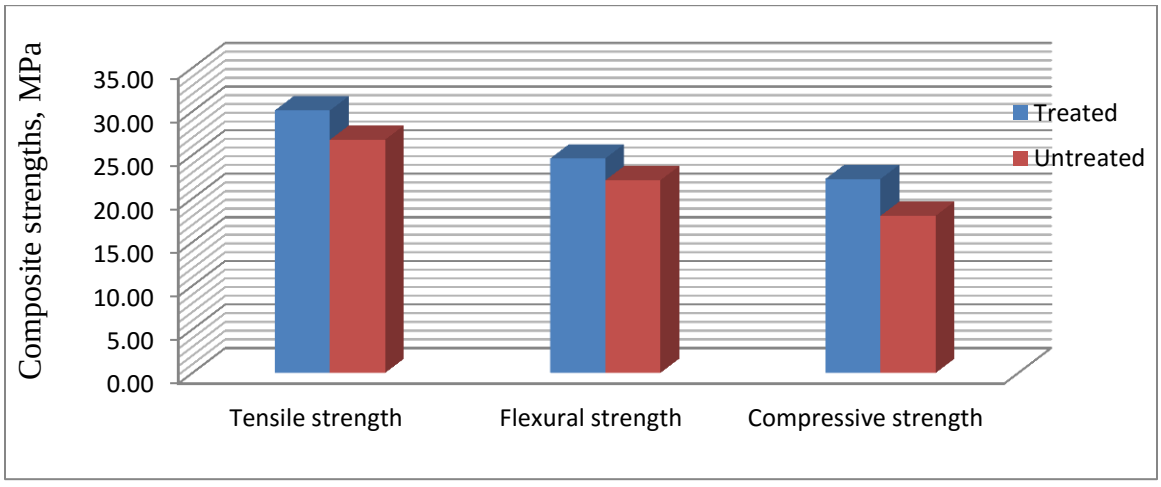

Figure 4.1: Effect of alkali treatment on the tensile, flexural and compressive strengths of the composites at 40wt.%

The study showed improved tensile, flexural and compressive strengths of the composites at same fibre weight fraction due to alkali treatment. For instance, at 40wt.%, the tensile, flexural and compressive strengths increased by 12.59%, 11.36% and 23.46% respectively. The improved tensile, flexural and compressive strengths can be attributed to improved fibre-matrix interface bonding due to removal of cementing materials such as lignin thus increasing fibre surface area. The improvement in strengths is also due to better mechanical interlocking between individual fibres resulting into increased strengths for treated composites compared to untreated composites.

b) *Effect of alkali treatment on tensile, flexural and compressive moduli of the composites at 40wt.%*

The tensile moduli for the woven sisal/epoxy composites showed maximum values of 5.29 GPa and 4.70 GPa for treated and untreated composites respectively at 50% fibre weight fraction. The maximum flexural moduli for the composites were 3.73 GPa (treated) and 3.06 GPa (untreated) at 60% fibre weight fraction. The composites showed maximum compressive moduli of 3.10 GPa (treated) and 2.90 GPa (untreated) at 60% fibre weight fraction. The effect of alkali treatment on tensile, flexural and compressive moduli of the composites at 40% fibre weight fraction is presented in Fig. 4.2.

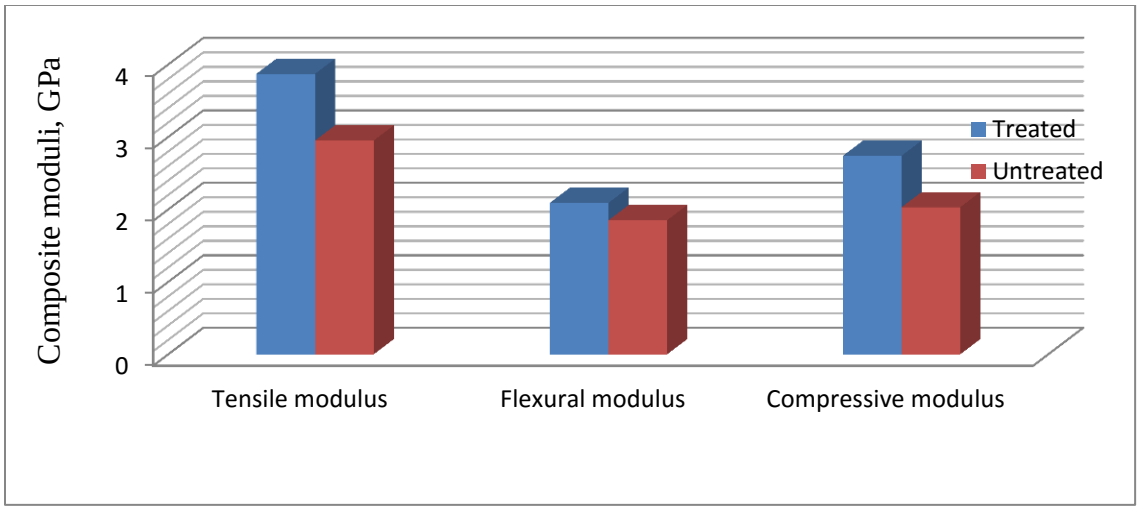

Figure 4.2: Effect of alkali treatment on the tensile, flexural and compressive moduli of the composites at 40wt.%

Alkali treatment of the sisal fibres resulted into improved tensile, flexural and compressive moduli of the composites. At 40wt.%, the tensile, flexural and compressive moduli of the composites increased by 31.19%, 12.97% and 34.98% respectively. Therefore, it can be deduced that alkali treatment of the sisal fabric improved the tensile, flexural and compressive moduli of the resultant composites. This is attributed to increased fibre surface area as a result of excellent fibre-matrix interfacial adhesion. Similar results on the effect of alkali treatment on tensile modulus have been reported in literature. For instance, Joseph et al., (1996b) working at 30% fibre content showed that the tensile modulus for alkali treated sisal fibre with low density polyethylene (LDPE) was 3.33 GPa compared to 3.09 GPa for untreated sisal fibres.

c) *Effect of alkali treatment on impact strength of the composites at 40wt.%*

It is clear from the obtained impact strength results that alkali treated composites showed higher impact strengths compared to corresponding untreated composites (see Fig. 4.3). For instance, at 40% fibre weight fraction, the impact strength of the treated composites

showed an increase of 28.67% compared to the neat composites. This can be attributed to increased energy absorption thus more energy is required to break the specimens resulting into improved impact strengths as compared to untreated composites.

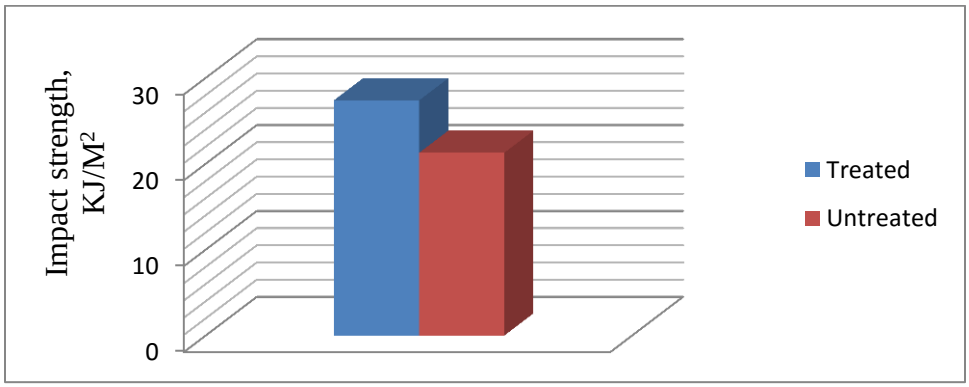

Figure 4.3: Effect of alkali treatment on the impact strength of the composites at 40wt.%

4.5 Effect of Fibre Weight Fraction on the Mechanical Properties of the Composites

a) Effect of fibre weight fraction on the tensile, flexural and compressive strengths of the composites

Fig. 4.4 shows the effect of fibre weight fraction on the tensile, flexural and compressive strengths of the composites.

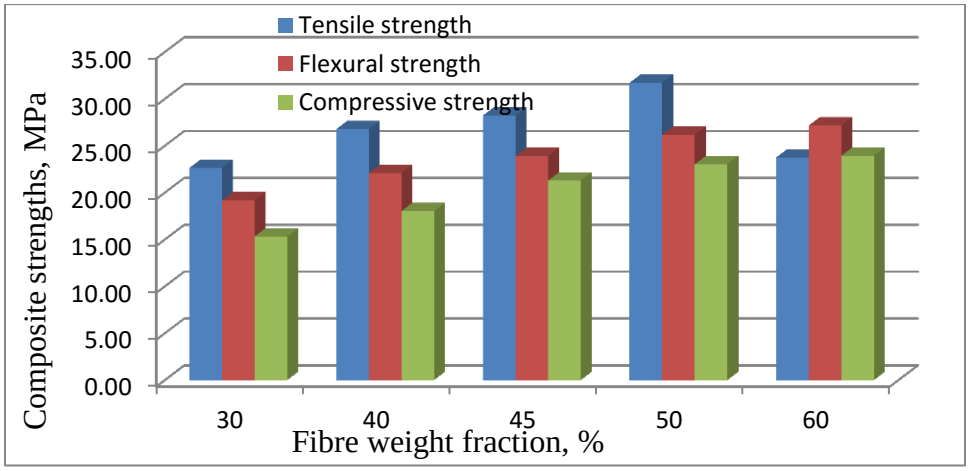

Figure 4.4: Effect of fibre weight fraction on tensile, flexural and compressive strengths of the composites

For tensile, flexural and compressive strengths, the composites showed increasing trend with increase in fibre weight fraction. For instance, the tensile strengths of the composites increased by 18.25%, 5.49% and 12.36% as fibre weight fraction increased from 30-40wt.%, 40-45wt.% and 45-50wt.% respectively. However, the tensile strength of the composites reduced by 25.13% as fibre weight fraction increased from 50-60wt.%. The observed increase in composite tensile strength with fibre weight fraction from 30-50wt.% can be attributed to increased amount of load bearing elements (fibres) in the composites as well as better fibre-matrix interface bonding. This ensures good stress transfer from the matrix to the fibres. However, at high fibre weight fraction (60wt.%), there was a reduction in tensile strength due to possible poor bonding of fibres by the matrix as a result of reduced wettability.

In general, the tensile strength results obtained in this research are comparable to those of sisal fibres reinforced polymer composites reported in literature. For example, the tensile strength of sisal reinforced polypropylene composite at 40% fibre loading was reported to be approximately 35 MPa (Wambua, 2003); 21 MPa (at 10 wt%) for sisal reinforced polyester composite (Fávaro et al., 2010); 34.27 MPa for longitudinally oriented LDPE-sisal composites (Joseph et al., 1996b); 44.40 MPa; 45.06 MPa and 31.12 MPa for sisal reinforced polypropylene, sisal reinforced polystyrene and sisal reinforced polyethylene respectively at 30 wt.% fibre content (Joseph et al., 1999).

Research findings using natural fibres in woven form have shown a slight improvement in tensile strength compared to same reinforcement in “loose fibre form”. For instance, a research on jute fabric reinforced epoxy composites reported a high tensile strength of 85 MPa while pure jute/epoxy composites showed tensile strength of 53.31 MPa at 40%

fibre loading (Jawaid et al, 2011). The high tensile strength observed in woven fabric reinforcement can be attributed to unidirectional orientation of fibres in the fabric hence minimal or no fibre overlapping resulting into maximum stress transfer from the matrix to the reinforcement. This allows these fibres to withstand high tensile loads hence show higher tensile strength as compared to reinforcement in "loose" fibre form.

The flexural strengths of the composites increased with fibre weight fraction. For instance, flexural strengths increased by 15.28%, 8.19%, 9.45% and 3.78% as fibre weight fraction increased from 30-40wt.%, 40-45wt.%, 45-50wt.% and 50-60wt.% respectively to attain maximum flexural strength of 27.16 MPa at 60wt.%. The observed increase in flexural strengths with increase in fibre weight fraction can be explained by increased fibre loading thus increasing the ability of sisal fibres to resist applied bending forces.

A similar trend of increasing composite flexural strength with fibre loading has been reported in literature; Ghani et al., (2012) working on pulped leaf/epoxy composite showed that increasing the content of pulped leaf fibres in the composites resulted into increase in flexural strength.

On the other hand, the compressive strengths increased by 17.69%, 18.08%, 8.17% and 3.95% as fibre weight fraction increased from 30-40wt.%, 40-45wt.%, 45-50wt.% and 50-60wt.% respectively to attain maximum compressive strength of 23.94 MPa at 60wt.%. This could be due to improved fibre-matrix interfacial adhesion as well as absence of voids at the fibre-matrix interface thus the composites are able to withstand higher applied compressive loads. That is, the more the interfacial bonding between fibre and matrix in the composite structure, the higher the values of compressive strength.

The reported increase in compressive strength with increase in fibre loading agrees with other results in the literature. The results by Sunil and Akbar, (2013) on natural fibres (sisal, hemp and mixture of sisal and hemp) reinforced composites with polymer resin showed that the compressive strength of all composites increased with the weight of fibre in the composites.

b) *Effect of fibre weight fraction on the tensile, flexural and compressive moduli of the composites*

Figure 4.5 shows the effect of fibre weight fraction on tensile, flexural and tensile moduli of the composites. The results showed an increase in the tensile, flexural and compressive moduli of the composites with increase fibre weight fraction.

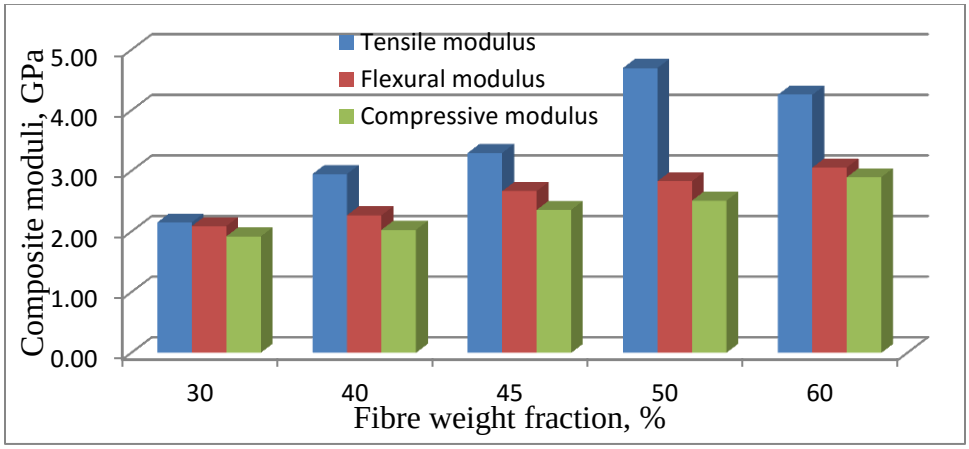

Figure 4.5: Effect of fibre weight fraction on tensile, flexural and compressive moduli of the composites

The tensile moduli of the composites increased by 37.21%, 11.86% and 42.42% as fibre loading increased from 30-40wt.%, 40-45wt.% and 45-50wt.% respectively. However, the tensile modulus reduced by 9.36% as fibre weight fraction increased from 50-60wt.%. The observed increase in tensile modulus with fibre content from 30-50wt.% can be attributed to increase in the amount of load-bearing elements, fibres, making the

composites stiffer. The decrease in tensile moduli as fibre weight fraction increased from 50-60wt.% could be due to poor wettability of fibres by the matrix at higher fibre loading making the composite less stiff to withstand applied tensile loads.

The existing literature on tensile modulus shows high degree of variations for instance, sisal polypropylene at 40wt.% showed tensile modulus of 5.8 GPa (Wambua, 2003). Sisal/polystyrene showed tensile modulus ranging between 390 MPa and 710.7 MPa as fibre loading increased from 0 to 30wt.%. The result further indicated that the tensile modulus of treated composites was higher than untreated composites (Manikandan et al., 1996). The variations in tensile modulus of sisal reinforced polymer composites can be attributed to the variations of mechanical properties of polymers used and variations of mechanical properties of sisal with respect to crop, location, climate, age and the section of the fibre strand. Other factors such as composite manufacturing techniques and testing parameters like speed and direction can be attributed to these wide variations in tensile modulus exhibited in the literature.

The compressive moduli of the composites increased by 5.73%, 16.26%, 6.36% and 15.54% as fibre weight fraction increased from 30-40wt.%, 40-45wt.%, 45-50wt.% and 50-60wt.%. Also, the flexural moduli increased by 8.61%, 17.62%, 5.99% and 8.13% as fibre weight fraction increased from 30-40wt.%, 40-45wt.%, 45-50wt.% and 50-60wt.% respectively. The increase in flexural and compressive moduli with increase in fibre loading in the composite may be due to high dispersion of fibres in the matrix. This indicates enhancement in stiffness of the composites as a result of incorporation of more fibres in the composites.

Similar results of increasing flexural moduli with fibre content have been reported in literature. For instance, Ramanaiah et al., (2012) studying the effect of fibre loading on mechanical properties of borassus seed shoot fibre reinforced polyester composites reported that flexural moduli increased from 1400-3700MPa as fibre loading increased from 0-0.305 fibre volume fraction.

However, the flexural moduli results were comparatively lower than the corresponding tensile moduli. The variations between tensile and flexural moduli can be explained by different types of stresses during testing. For tensile testing, the stresses are uniformly distributed throughout the cross sectional area of the specimen while in flexural testing the flexure stresses vary from zero in the middle to maximum in the bottom (tensile) and top (compressive) surfaces of the test specimen (Folkes, 1985).

c) Effect of fibre weight fraction on the impact strengths of the composites

Fig. 4.6 shows the effect of fibre weight fraction on impact strengths of the composites.

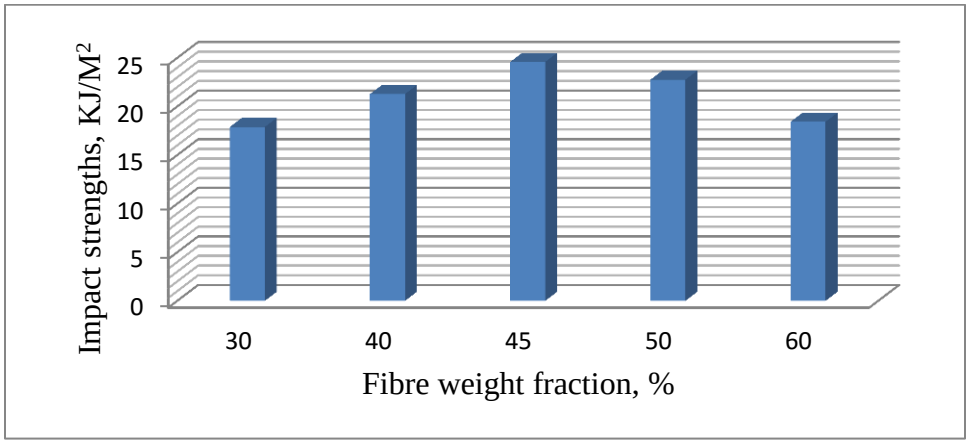

Figure 4.6 Effect of fibre weight fraction on the impact strengths of the composites

The impact strengths increased by 18.95% and 15.51% as fibre weight fraction increased from 30-40wt.% and 40-45wt.% respectively to attain maximum impact strength of 24.58 KJ/m^2 at 45wt.%. The increasing trend of impact strength with increasing fibre content

from 30 to 45% fibre loading is due to the increase in fibre content as well as increase in compressive pressure thus eliminating void contents in the composites. However, the impact strengths decreased by 7.45% and 19.03% as fibre weight fraction increased from 45-50wt.% and 50-60wt.% respectively. Reduction in impact strength beyond 45% fibre loading is due to insufficient fibre-matrix interface bond hence the composites cannot withstand high impact loads.

The findings in this research agree with research by Zhong, Lv and Wei (2007) whereby the impact strength increased with increase in fibre loading from 30-50wt% and drastically decreased as fibre loading increased to 60wt%, with maximum impact strength at 50wt% fibre loading. This is further supported by research findings on natural fibre reinforced polymer composites that have shown an increasing trend in impact strength with increase in fibre loading. For instance, Wambua et al., (2003) studied the Charpy impact strength of kenaf reinforced polypropylene composites as a function of fibre weight fraction. They observed a moderate increase in impact strength as loading increased from 30-40wt% followed by a sharp increase between 40 and 50wt% with a large serrated fracture surface observed at 50wt% as compared to composites at 30wt%.

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The following conclusions can be drawn from the results of the mechanical properties of woven sisal reinforced epoxy composites:

1) The tensile properties i.e. strength, tenacity and elongation at break of the fabric reinforcement were higher for warp yarns when compared to weft yarn. Also, woven fabric reinforcement sustained higher tensile loads when loaded along the warp direction than in the weft direction. This observation can be attributed to sizing chemicals such as starch mainly applied on warp yarn to improve their performance since the warp yarns are subjected to mechanical abrasion during weaving.
2) Alkali treated composites showed higher mechanical properties compared to untreated composites. This is because alkali treatment of sisal fibres reduces the number of cellulose hydroxyl groups in the fibre-matrix interface thus resulting into improved fibre-matrix interfacial adhesion. Secondly, alkali treatment improved the surface roughness of sisal fibres causing better mechanical interlocking between fibres, thus, improving the mechanical properties of the composites.
3) The mechanical properties of sisal reinforced epoxy composites increased with increasing fibre weight fraction regardless of the number of layers in the composites. For example,
    i). Tensile strength increased with fibre weight fraction from 30% to 50%V_{wf}. This can be explained by increased amount of load bearing elements, fibres, in the composites as well as excellent fibre-matrix interfacial adhesion that ensure good stress transfer from the matrix to the fibres. However, as the fibre

weight fraction increased from 50-60% fibre loading, there was reduction in tensile strength due to possible poor bonding of the fibres by the matrix as a result of reduced wettability.

ii). The flexural strength increased with increase in fibre weight fraction from 30% to 60%. This phenomenon of increasing flexural strength with increase in fibre weight fraction can be explained by increased fibre content in the composite thus increasing the ability of sisal fibres to resist applied bending loads.

iii). The impact strength increased with fibre weight fraction up to 45%V_{wf} due to increase in fibre content as well as increase in compressive pressure thus eliminating void contents in the composites. However, the impact strength decreased as fibre weight fraction increased from 45% to 60% fibre loading due to insufficient fibre-matrix interface bond hence the composites could not withstand high impact loads.

iv). The compressive strength increased as fibre loading increased from 30% to 60%V_{wf}. This can be attributed to improved fibre-matrix interfacial adhesion as well as absence of voids at the fibre-matrix interface thus the composites are able to withstand higher applied compressive loads.

5.2 Recommendations

1. Apart from alkali treatment aimed at eliminating cellulose hydroxyl groups present in the fibre-matrix interface causing poor mechanical properties and high rate of water absorption, other fibre surface treatments such as silane treatment and acetylation of natural fibres have been recommended for further study whose results will be

compared with the results of alkali treatment of this study with the objective of establishing the most effective fibre treatment method.

2. The fabricated woven sisal fabric reinforced composites showed good mechanical properties hence can be used as ceiling boards and portioning boards. Since these boards could be subjected to different in service environmental conditions of temperature and humidity, physical tests such as water absorption, flammability and burning tests have been recommended for further study.

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