FABRICATION AND DETERMINATION OF MECHANICAL AND THERMAL PROPERTIES OF SISAL/CATTAIL FIBRE REINFORCED POLYESTER HYBRID COMPOSITES

BY

MBECHE SILAS MOGAKA

B.Tech. (Hons) Moi University, Grad. Eng. EBK

A THESIS SUBMITTED TO THE SCHOOL OF ENGINEERING IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR AWARD OF

THE MASTER OF SCIENCE DEGREE IN INDUSTRIAL ENGINEERING

DEPARTMENT OF MANUFACTURING, INDUSTRIAL & TEXTILE ENGINEERING

MOI UNIVERSITY, ELDORET

AUGUST, 2020

DECLARATION

DECLARATION BY THE STUDENT

This thesis is my original work and has not been presented for a degree in any other University. No part of this thesis may be reproduced without the prior written permission of the author and/or Moi University.

Mbeche Silas Mogaka   Date

TEC/PGMT/05/18

DECLARATION BY SUPERVISORS

This Thesis has been submitted with our approval as University supervisors.

Prof. (Eng.) Paul M. Wambua, FIEK   Date

Department of Manufacturing, Industrial & Textile Engineering, Moi University,

P.O Box 3900-30100, Eldoret-Kenya

Dr. David Njuguna Githinji   Date

Department of Manufacturing, Industrial & Textile Engineering, Moi University,

P.O. Box 3900-30100, Eldoret-Kenya

DEDICATION

To

My Mother Mrs Alice Nyaboke Mbeche;

My Late Father Mr Jackson Mbeche Masore;

My loving wife Eucabeth Mosero Mochere;

My children, Avidan Mbeche and Adriel Mochere;

For your Love, Support & Encouragement.

ABSTRACT

Due to global environmental pollution and high energy consumption, researchers have been stimulated to seek for sustainable materials that can replace non-biodegradable and environmentally unfriendly materials in reinforced composites. Natural fibre-reinforcements seem to be good alternatives since they are biodegradable, abundant, inexpensive and have excellent physical and insulation properties and high strength to weight ratio. Therefore, sisal and cattail fibres provide a better alternative. Kenya produces about 25,310 tons of sisal fibres annually. Furthermore, cattail plant (*Typha angustifolia*) is a common marginal weed in Kenyan wetlands. The aim of this work was to fabricate a fibre reinforced polyester hybrid composite from a blend of cattail and sisal fibres (alkali treated and untreated), to investigate the properties of these fibres and the effects of varying the ratios on the mechanical and thermal properties of the hybrid composites. The percentages of cattail and sisal fibres in the blend were varied from 0-100% (100/0,75/25,50/50,25/75,0/100) and moulded into hybrid composites using hand lay-up technique. Curing was carried out for 6 hours at room temperature under a pressure of 3.27kN/m^2. The hybrid fibre weight fraction (wt.%) and cattail/sisal blend ratio were varied in order to determine their effects on the mechanical and thermal properties of the hybrid composites. Alkali treatment of the resultant composite was done by soaking some fibres in 4%w/v NaOH solution (sisal) and 5%w/v NaOH solution (cattail) for one hour at room temperature. Test specimens were prepared according to ASTM D638, ASTM D3410, ASTM D790, ISO 179 and ASTM C518 standards. Tenacity of treated sisal (146.26cN/tex) and cattail (35.35cN/tex) fibres was higher than that of untreated sisal (23.52cN/tex) and cattail (9.46cN/tex) fibres, while the linear density of treated sisal (10tex) and cattail (12.33tex) fibres were lower than 26.17tex and 35.17tex for the untreated fibres respectively. The flexural, tensile and compressive strengths of the hybrid composites increased as the proportion of sisal fibres was increased from 0-75% giving peak values of 45.97MPa, 32.39MPa and 25.43MPa respectively. Impact strength increased as the percentage of sisal fibres in the hybrid was increased from 0-100% to attain a maximum value of 34.40kJ/m^2. Composites fabricated with alkali-treated fibres had better strengths (tensile-33.82MPa, flexural-45.68MPa, compressive-24.98MPa and impact-27.08kJ/m^2) than those fabricated with untreated fibres (28.89MPa, 36.65MPa, 21.05MPa and 23.19kJ/m^2 respectively). Cattail/polyester composites showed lower thermal conductivity (0.31W/mK) compared to 0.56W/mK for sisal/polyester composites. The mechanical and thermal properties recorded in this study indicate that these hybrid composites may be used for non-structural applications (as ceiling boards, walls, room partitioning, door panels and electronic and food packaging). However, further studies on their physical properties such as water absorption and flammability tests are required.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGEMENTS

My special heartfelt thanks and glory to the Almighty God for keeping me in good health throughout my MSc studies.

Special appreciation goes to various individuals and institutions for their overwhelming support rendered during my MSc studies. Thanks are due to the Africa Centre of Excellence II in Phytochemicals, Textile & Renewable Energy (ACE II-PTRE) of Moi University, Kenya for the scholarship without which, my studies would have not been possible. To my supervisors: **Prof. (Eng.) Paul M. Wambua (FIEK)** and **Dr. David N. Githinji** for their selfless intellectual support, encouragement, timely feedback and patience throughout my research work.

Special appreciation to the Department of Mechanical Engineering, Moi University-Kenya for allowing me to fabricate my mould from their workshop. I am grateful to Rivatex (East Africa) Limited, Multimedia University (MU), Jomo Kenyatta University of Technology (JKUAT) for allowing me to carry out testing of specimens in their laboratories.

Lastly, I am always grateful to my family. My Mother Mrs Alice Nyaboke Mbeche and Late Father Mr Jackson Mbeche Masore for showing me the light of education. To my beloved and ever-supporting wife **Mrs Eucabeth Mosero Mochere** and my children: **Avidan Mbeche** and **Adriel Mochere** for their continuous support and encouragement in all my academic endeavours. I sincerely thank you for the time you accorded me in pursuit of this degree. This was a time I could have spent responsibly with you as a caring husband and father respectively. May God bless you all abundantly.

LIST OF ACRONYMS

ASTM	American Standard for Testing and Materials
ISO	International Standard for Organization
MR-8	Mould Release Agent
MEKP	Methyl Ethyl Ketone Peroxide
UPR	Unsaturated Polyester Resin
ULF	Unidirectional Long Fibres
PP	Polypropylene
NaOH	Sodium Hydroxide
GPa	Giga Pascal (10^9 Pa)
NFC	Natural Fibre Composites
EPS	Expanded polystyrene
XPS	Extruded polystyrene
SEM	Scanning Electron Micrograph
GFRP	Glass Fibre Reinforced Polymer

CHAPTER ONE: INTRODUCTION

1.1 Background of the Study

A composite is an engineered material made from two or more constituent materials with significantly different physical or chemical properties combined together to form a resultant material with features that are different from the individual components (Figure 1.1). On the other hand, hybrid composites are engineered composite materials consisting of two or more fibres as reinforcements with the aim of exploiting different properties of these fibres while retaining their individual characteristics and properties in the resultant product. For a long time, fibres such as carbon, glass and aramid have dominated the composite manufacturing sector. This is predominantly because of their relatively superior mechanical and thermal properties. However, with increasing environmental concerns, researchers have investigated the possibility of replacing them with natural fibres in the manufacture of composites. Research has been done using natural fibres such as coir, sisal, banana, jute and cattail, investigating the possibility of using them as reinforcements in composites for non-structural applications. Natural fibre-reinforced composites (1) uses renewable raw materials, (2) are combustible, (3) have low density, (4) possess good thermal properties, (5) are bio-degradable, (6) are non-toxic, (7) low cost and (8) have great performance. Therefore, natural fibre reinforced composites form a new class of materials with desired properties which can substitute scarce wood in many non-structural applications such as ceiling boards, walls, room partitioning, door panels, electronic and food packaging (Asdrubali et al., 2015; Bajwa et al., 2015; Ramanaiah et al., 2011).

Leafiran fibres are fibres obtained from cattail plant (*Typha angustifolia*) leaf. Cattail plant grows in the wildly, mostly in wetlands i.e. riverbanks, shorelines, along slowmoving streams and in areas with fluctuating water levels such as dams or roadside ditches. Fibre extraction is done first by retting process where the cattail leaves are cut at their base and immersed in a water-retting tank for two weeks. After, the fibres are manually stripped from the leaves, washed and dried (Mortazavi & Moghadam, 2009; Ramanaiah et al., 2011). The properties of leafiran fibres are similar to that of hemp or jute and therefore can be equivalently used in the textile industry. However, cattail fibres have not been adequately studied (Mortazavi & Moghadam, 2009).

Sisal fibres on the other hand are extracted from sisal (*Agave sisalana)* leaves. The fibres are hard and are among the widely used natural fibres because of their availability. Each sisal plant produces 200-250 leaves and each leaf contains 1000-1200 fibre bundles (Mukherjee & Satyanarayana, 1984). Sisal fibres can easily be extracted from sisal leaves by retting and decortication. Additionally, the fibres are readily available, cheap, easily biodegraded and are of great performance. Sisal has competitive mechanical properties as compared to some other natural fibres which is the reason of hybridising them with cattail fibres in this research. Figure 1.1, shows the composition of a composite material: matrix, reinforcement and the interface between the two.

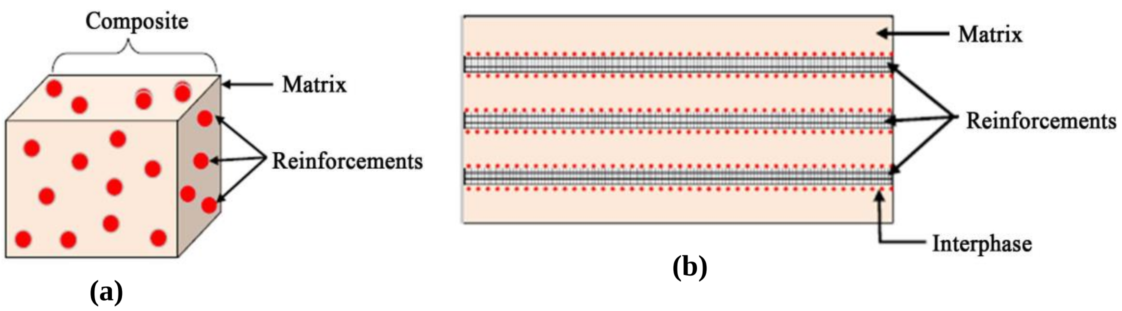


Figure 1.1: (a) Randomly oriented composite showing a matrix and fibre reinforcements and (b) shows an inter-phase of matrix and reinforcements (Ashik & Sharma, 2015)

1.2 Statement of the Problem

Many Kenyans rely on plastic/wood products in their day-to-day activities. However, the use of these products causes more harm to the environment and health hazards to humans and animals as well as land degradation. This is because of the non-degradable nature of these products, which make their disposal difficult.

Recently, researchers have investigated the possibility of substituting these products with natural fibre-reinforced composites for use in manufacturing of panels for packaging (electronic and food), automobiles parts and insulation boards for construction (ceiling and partitioning). The use of these natural fibres as reinforcements require fibres that are readily available and with unique physical and mechanical properties. In this research, a natural fibre-reinforced hybrid composite with better properties compared to wood, plastic or synthetic fibre reinforced composites was fabricated.

Cattail and sisal fibres were used as alternative natural fibre reinforcements in the fabrication of natural fibre-reinforced composites. Therefore, the primary purpose of this research was to fabricate and characterize cattail/sisal fibre reinforced hybrid composites with the aim of utilizing the desirable properties of the two fibres. Analyzed properties of the resultant composite properties were compared with those reported in literature to determine its applicability.

1.3 Justification of the Research

Cattail is a plant of *Typha* genus that widely grows in swamps, ponds, rivers and lakes in most parts of Kenya such as Nairobi, Lugari and Busia (Phanice et al.,2016; Plagens, 2016). It is considered a marginal weed which can grow to heights of 3 to 10 feet. It is a dominant plant in most wetlands and its control can be difficult due to its rapid growth and spread through pollination and root system. The growth rate and yield of cattail plant is enormous as reported by Krus et al. (2014). It has an annual production of between 15-20 tonnes of dry matter per hectare, which is much higher than what forests can produce (Krus et al., 2014). Due to this, it is evident that the plant is abundantly available in nature and is renewable. Cattail leaf fibre reinforced composites have been found to have a lower thermal conductivity ranging between 0.0438-0.0606 W/mK as compared to composites of other natural fibres and therefore making cattail fibres an ideal raw material for thermal insulation composites (Luamkanchanaphan et al., 2012).

Sisal fibres are readily available with a global annual production of about 161,160 tons (from the four major producing countries i.e. Brazil, Kenya, Tanzania and Madagascar)("Committee on Commodity Problems Joint Meeting of the Thirty-Ninth Session of the Forty-First Session of the Intergovernmental Group," 2017). Kenya produces approximately 25,310 tons of sisal per year according to the Committee on Commodity Problems Joint Meeting of the Thirty-Ninth Session of the Forty-First Session of the Intergovernmental Group (2017). On account of its high specific strength and modulus as compared to cattail fibres (Pickering et al., 2016) as well as its availability, sisal fibre is a promising natural reinforcement in hybrid composites. The good mechanical properties of sisal fibres and good insulation properties of cattail fibres could complement each other to yield hybrid composites with enhanced mechanical and thermal properties.

Unsaturated polyester resin mixed with the hardener was used as a matrix. Polyester was selected because of its high strength upon curing. Cross-linking reaction takes place to form strong chemical bonds which cannot be easily destroyed upon exposing the hybrid composite to high temperatures. Polyester resin has many advantages compared to other resins such as excellent adhesion, low thermal conductivity, good corrosion resistance, processing versatility and low shrinkage. Therefore, the production of sisal/cattail-based composites will add value to both cattail plant and locally produced sisal. The use of cattail weed in the production of sisal/cattail hybrid composites will control its invasive growth in water bodies as well as create employment opportunity. Moreover, environment pollution will be reduced and both wetlands and Kenyan forests will be conserved due to use of cattail plant as a raw material.

1.4 Objectives of the Study

1.4.1 General Objective

To fabricate and determine the mechanical and physical properties of sisal/cattail fibre reinforced polyester hybrid composites.

1.4.2 Specific Objectives

i. To characterize mechanical and physical properties of sisal and cattail fibres.

ii. To produce sisal/cattail fibre reinforced polyester hybrid composites.

iii. To determine the effect of varying hybrid (cattail + sisal) fibre weight fraction (wt.%), percentage of sisal/cattail fibres (%) in the blend and the effect of alkali treatment on the mechanical and thermal conductivity properties of the composites.

iv. To investigate the mechanical (flexural, tensile, compression and impact) and thermal conductivity properties of the composites.

1.5 Project Methodology

This involved production of composites using a simple hand lay-up technique utilizing a blend of sisal and cattail fibres as reinforcements, unsaturated polyester resin and hardener followed by determination of mechanical and thermal conductivity properties of the resultant sisal/cattail hybrid composites.

1.6 Scope of the Study

This research is limited to the fabrication of sisal/cattail fibre reinforced hybrid composites using hand lay-up method and investigation of their mechanical (i.e. flexural, tensile, compression and impact) properties and thermal conductivity. Sisal and cattail fibres were manually extracted from their respective leaves and characterized in terms of linear density and tensile properties. Unsaturated polyester resin and Methyl Ethyl Ketone Peroxide (MEKP) hardener were used as the matrix. The effect of layering pattern on the mechanical properties of the composite is outside the scope of the current study.

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

With growing environmental concerns, demand for biodegradable and recyclable materials has increased. Due to this, natural fibres are considered as possible replacements of synthetic fibres as reinforcements in polymer composites. As scientists are focused on this matter, more research is being done on finding new fibres especially from underutilized natural resources such as cattail plant and studying the possibility of using them in structural and non-structural applications (Mortazavi & Moghadam, 2009).

2.2 Characterization of Natural Fibres

Natural fibres are fibres directly obtained from animals, plants and minerals. Plant fibres are obtained from various parts of the plant. The most commonly used plant fibres in composite manufacture are coir, sisal, jute, banana, pineapple, maize stalk, flax and hemp (Athijayamani et al., 2010).

Most often, natural fibres including sisal and cattail are composed of 50-80% cellulose, 5-20% lignin and up to 20% moisture content. The cell wall for most natural vegetable fibres consists of a hollow tube with four different layers i.e. lumen, one thin primary cell wall and three secondary cell walls (Figure 2.1). These layers are composed of cellulose covered with hemicellulose and lignin as a matrix. However, this structure and content of the cell wall differs from one species to another and between different parts of the plants. Mechanical properties of natural fibres are determined by their cellulose content via hydrogen bonds and other linkages, structure of fibres, angle of fibrils and cross section. The secondary layer consists of three layers and therefore the thickest and great contributor (of about 80%) of the overall properties of a fibre. This is because it is formed by microfibrils, which contain larger quantities of cellulose molecules (Akil et al., 2011).

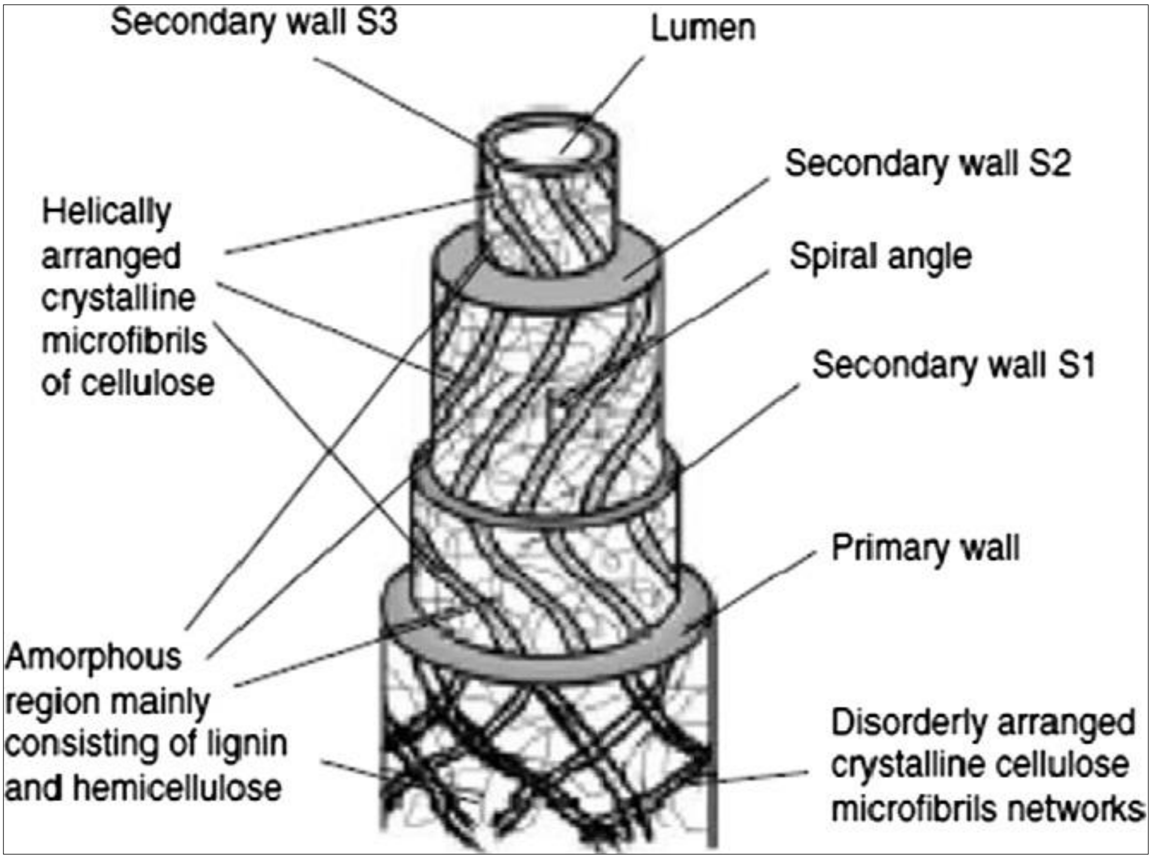


Figure 2.1: Schematic picture of natural plants cell wall (Akil et al., 2011)

2.2.1 Cattail leaf fibre

Cattail leaf fibre is obtained from cattail plant, which belongs to *Typha* genus which is mostly grows in wetlands like river banks and shorelines. Because Kenya has many wetlands, the weed is available in abundance in nature and is a renewable resource (Phanice et al., 2016; Plagens, 2016). The image of cattail plant is shown in Figure 2.2.

(a) **(b)**

Figure 2.2: (a) The image of the *Typha* plant (b) *Typha* plants growing on a wetland (Liu et al., 2017)

Akil et al. (2011) investigated the tensile strength, chemical composition (Table 2.1), thermal properties and moisture absorption of leafiran fibres. They reported it is a natural cellulosic fibre with similar structure like other common cellulosic natural fibres and with an initial modulus of 140-200N/tex, a tensile strength of 25-35cN/tex and an elongation at break of 1.2-1.6%. Additionally, the fibres;

- Were lignocellulosic in nature (54% cellulose and 28% lignin content)
- Had a low density of 1.26 g/cm^3
- Possessed relatively higher moisture regains ranging between 8.5-10%
- Had good thermal stability

Table 2.1: Leafiran fibre composition (Mortazavi & Moghadam, 2009)

	ADF (%)	CV (%)	NDF (%)	CV (%)	NCWM (%)	CV (%)	Hemi (%)	CV (%)	Cellulose (%)	CV (%)	Lignin (%)	CV (%)
Typha leaf	53.28	1.62	74.85	2.86	25.15	1.68	21.42	4.3	35.83	3.45	17.60	5.7
Leafiran fibre	82.63	1.44	92.37	1.61	7.62	5.46	9.87	7.6	53.47	8.5	28.54	5.9

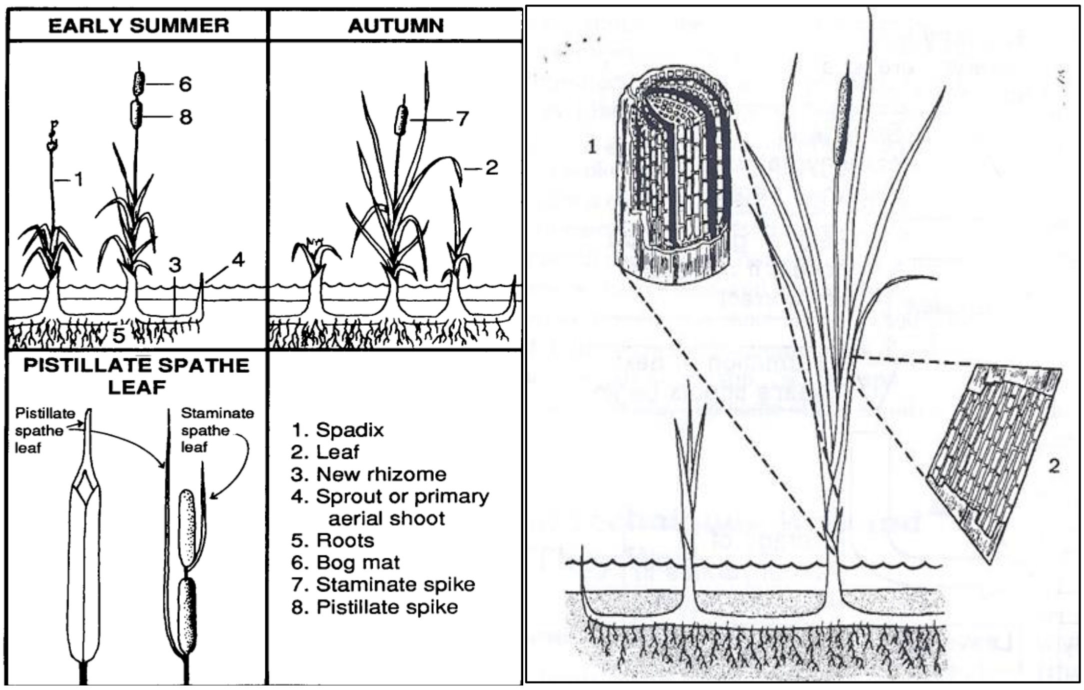
ADF-Acid Detergent Fibre; NDF-Natural Detergent Fibre; NCWM-Non-Cell Wall Material; Hemi-Hemicellulose.

Chakma et al. (2017) carried out a study on cattail fibre extraction efficiency, its quality and characterization. From their study, it was reported that the whole cattail plant (stem and leaves) under controlled experiment conditions (1% NaOH and Material Liquor Ratio of 1:50) could be transformed into textile fibres with a fibre yield of 78% at 60^0C for 6 hours. Further, they found that: (i) the crimp-adjusted fibre length and cattail plant length are similar, (ii) diameter of cattail fibre is similar to that of cotton, (iii) cattail fibre burning behaviour is similar to that of cotton while its decomposition temperature is higher than that of cotton, (iv) cattail fibre's moisture regain (%) was found to be ≈10% at 60% RH and 25°C and (v) Scanning Electron Micrographs (SEM) indicated a unique sub microscopic 'crenelated' structure and therefore can be used for textile and non-textile applications such as insulation and biomedical.

Rezig et al. (2014) extracted and characterized Tunisian *Typha* leaf fibres. The researchers extracted the fibres using a hot bath solution of NaOH (concentration ranging between 10 and 30g/L). Their extraction bath consisted of 5g cattail leaf fibres, a Material Liquor Ratio of 1:40, an operating temperature of 80-120^0C and a treatment period of between 2 and 4 hours. The extracted fibres were then thoroughly cleaned with warm water to remove all soluble impurities. Thereafter, the fibres were neutralized with 10ml/L acetic acid and rinsed with distilled water until they were free from NaOH. From their study, an optimal tenacity of 15.1cN/tex of the fibres was reported at 30g/L NaOH, 100 ^{0}C for a duration of 4 hours.

Moghaddam and Mortazavi (2016) evaluated the physical and chemical properties of leafiran fibres extracted with various conditions i.e. alkali solutions (potassium and sodium hydroxide), retting process (time and temperature) and nature of cattail leaf (dry or fresh green). Their results revealed better tensile properties and appearance for leafiran fibres extracted from fresh green leaves than those obtained from dry leaves.

Cao et al. (2016) investigated the possibility of using cattail fibres for oil sorption by studying their structure (Figure 2.3) and wetting characteristics. The team inferred that a single cattail fibre's fineness and average length varied between 10-17.5 μm and 7.9±1.2 mm respectively.



(a) **(b)**

Figure 2.3: (a) The structure of a cattail plant (b) cross-section of cattail stem (1) and longitudinal of a leaf (2) showing aerenchyma tissue (Sojda & Solberg, 1993)

As shown in Figure 2.3 (b), the leaves of cattail plant are rich in aerenchyma tissue (air spaces) which make the fibres an excellent insulating material (Sojda & Solberg, 1993). Some countries like Netherlands have gone ahead to investigate the possibilities of planting cattail plant with several paludiculture plots coming up. Production of extra cattail plant (apart from the one growing wildly in wetlands) is focused on a number of applications (Sojda & Solberg, 1993);

i. Manufacture of insulation materials.
ii. Fodder production for cattle and other livestock.
iii. Biological control of some insects which feed on cattail pollen.

However, the most valuable of the mentioned applications is the production of insulation materials.

2.2.2 Sisal fibres

Sisal fibre is extracted from the sword shaped leaves of *Agave sisalana* (sisal) plant. It is considered a hard fibre and one of the widely used natural fibres in most parts of the world. Sisal plant grows to a height of about 2m and can wildly grow along the roads, railway lines or are planted in farms especially in tropical countries. Each plant produces 200-250 leaves before flowering and each leaf contains approximately 700-1400 fibre bundles. Furthermore, the sandwich structure of the fibre leaf consists of approximately 4% fibre, 1% cuticle, 8% dry matter and 87% water (Silva et al., 2008). Fibre extraction is carried out using decorticators after which the fibres are washed and sundried.

The fibres from *Agave* leaves are smooth, yellow and straight with a diameter of 200-400 μm and length of 1-1.25 m. The mechanical properties of these fibres degrade when exposed to high temperatures and salty water. From the study done by Mancinoa et al. (2018), it was found that fibres obtained from 'medium third' of the sisal leaves had better mechanical properties. This is a clear indication that mechanical properties of sisal fibres are not uniform along their length. That is, fibres extracted from the tip have moderate properties, those from the midspan are stronger and stiffer and those from the lower part of the leaf have lower modulus and tensile strength but with advanced fracture strain. Silva et al. (2008) investigated the tensile behaviour of sisal fibres using a microforce testing system with four different gauge lengths and found the fibre Young's modulus to be about 18 GPa. Further, they found that strain-to-failure decreased from approximately 5.2% to 2.6% when there is an increase of gauge length from 10 mm to 40 mm.

Phologolo et al., (2012) investigated the chemical and mechanical properties of Kenyan sisal and from the study, they found it to contain a higher percentage of lignin (10-13%) and hemicellulose (18%). Further, the tensile strength was found to be 450 MPa with an elongation of between 3.9-5.17% and therefore comparable to sisal from other countries.

2.3 Natural Fibre Composites (NFC)

2.3.1 Cattail Composites

Mechanical and thermal conductivity of narrow-leaved cattail (*Typha angustifolia* L.) natural fibre-reinforced polyester composites fabricated by hand lay-up technique were investigated by Ramanaiah et al., (2011). The density and thermal conductivity of the composites were found to decrease with increasing fibre content but the mechanical properties improved. Decrease of thermal conductivity of the composite with increase of the fibre content is a clear indication that the fibre being used had a lower thermal conductivity.

Luamkanchanaphan et al. (2012) studied the physical, mechanical and thermal properties of insulation boards reinforced by narrow-leaved cattail fibres using methylene diphenyl diisocyanate (MDI) as a binder. Their results agreed with the findings of Ramanaiah et al. (2011) even though a different resin was used. They reported that the thermal conductivity of a composite with a density of 200-400 Kg/m^3 ranged from 0.04-0.06

W/mK. The team concluded that insulation composites from narrow-leaved cattail fibres yielded excellent and environment friendly insulating components that can be used in the construction industry than boards of other insulation materials. Further, Krus et al., (2014) fabricated insulation panels using cattail leaves and found them to have a closely comparable thermal conductivity of 0.05 W/mK to other materials (Table 2.2) and therefore giving its design good recommendation.

Table 2.2: Thermal conductivity of various materials (Asdrubali et al., 2015; Luamkanchanaphan et al., 2012)

Board Type	**Density (Kg/m^3)**	**Thermal Conductivity k (W/mK)**
Narrow-leaved cattail fibre	200-400	0.0438-0.0606
Wheat straw board	150-250	0.0481-0.0521
Cotton stalk fibre	150-450	0.0585-0.0815
Durian peel & coconut coir	311-611	0.0728-0.1117
Kenaf	100-250	0.040-0.065
Expanded perlite	78-224	0.0477-0.0616
Vermiculite	80-200	0.047-0.07
Pineapple leaves	178–232	0.035–0.042
Reeds	130–190	0.045–0.056

As shown in Table 2.2, the capacity of cattail leaf fibre insulation material stands out as compared to other organic insulation materials. In addition, Table 2.3 lists some of the unconventional building insulation materials that have so far been investigated.

Table 2.3: Some unconventional building insulation materials (Asdrubali et al., 2015)

Natural			**Recycled**
Reeds	Durian	Straw bale	Glass foam
Bagasse	Oil palm fibre	Sansevieria fibre	Plastics
Cattail	Pineapple leaves	Rice	Textile Fibres
Corn cob Cotton	Date Palm	Sunflower	

Therefore, cattail leaf fibre (as a natural unconventional insulation material) can be closely compared to some of the conventional insulation materials in Table 2.4.

Table 2.4: Thermal properties of some conventional insulation materials (Asdrubali et al., 2015)

	Density (Kg/m^3)	**Thermal Conductivity (W/mK)**
Rock wool	40-200	0.033-0.040
Expanded polystyrene (EPS)	15-35	0.031-0.038
Extruded polystyrene (XPS)	32-40	0.032-0.037
Kenaf	30-180	0.034-0.043
Sheep wool	10-25	0.038-0.054

The use of cattail fibres as reinforcement in polymer composites will not be in conflict with any agricultural activity as the plant is abundantly available in most wetlands (Asdrubali et al., 2015; Phanice et al., 2016; Plagens, 2016)

Use of insulation materials is nowadays common as an effective way of saving energy as they have the ability to reduce the heat conduction rate. Due to health concerns over inorganic insulation materials like glass fibre, research is being done to find alternative ways of using natural fibres (Luamkanchanaphan et al., 2012) where cattail fibres have been considered due to their benefits such as renewability, low toxicity, bio-degradability, good insulation properties and abundance (Krus et al., 2014; Luamkanchanaphan et al., 2012; Ramanaiah et al., 2011; Wuzella et al., 2011). This is further supported in the study done by Krus et al., (2014) on new sustainable cattail insulating building material made from magnesite-bound *Typha* boards. From their study, installation of these cattail composites in the building framework with a wall thickness of 20 cm led to a thermal transmittance coefficient of approximately 0.35 W/m^{2}K, which is extremely good and worthwhile to be used in the construction industry. Furthermore, production of cattail fibres is simple and environment friendly as compared to most traditional inorganic insulating materials.

The research done by Bajwa et al., (2015) on mechanical properties of cattail/wheat fibre reinforced poly methylene diphenyl diisocyanate (PMDI) composite reported superior mechanical properties than a 100% wheat straw or cattail composites in flexural stiffness, strength, internal bond and water absorption tests. Further, they proved that a blend of cattail leaf fibres with other fibres produces composites with superior mechanical properties. Cattail fibres can therefore be used as an alternative raw material in the manufacture of natural fibre reinforced hybrid composites.

A part from their average mechanical properties and low insulation properties, cattail leaf fibres have a remarkable self-gluing property due to their natural constituents that act as an intrinsic binder. Therefore, composites can be made from cattail leaf fibres without addition of any binder (Wuzella et al., 2011).

Wuzella et al., (2011) studied the properties of cattail leaf fibres by making green bio-based composites without adding any binder from the cattail leaves. The researchers tested various mechanical properties (flexural strength, flexural modulus elasticity) and surface textural properties and compared them with other natural fibre-reinforced composites. They concluded that binder-free cattail composites exhibit good mechanical and surface textural properties and therefore have potential to be used in automotive, furniture and building industries (Table 2.5).

Table 2.5: Flexural modulus of elasticity (MOE), and flexural strength of various natural fibre composites bonded with phenolic (PF) binder resin compared to binder-free produced *Typha*-based panels

Fibre mixture	Binder	Resin content (%)	Ra	Rt	Flexural MOE (MPa)	Flexural strength (MPa)
Kenaf (100%)	PF	15	25.27±2.18	289.04±35.73	932.5±1190	22.5±14.0
	PF	30	24.00±4.88	300.23±74.51	4343±1064.5	53.8±12.1
Flax (100%)	PF	15	12.89±1.18	136.45±11.07	574±230	17.4±3.2
	PF	30	13.37±0.36	159.49±12.00	4839±886.5	47.5±13.5
Hemp (100%)	PF	15	20.90±2.19	259.77±50.24	2276.5±230	37.9±9.0
	PF	30	20.72±1.63	260.20±39.80	6186.5±500	73.3±4.5
Coco (100%)	PF	15	32.57±2.87	351.82±41.85	n.d.	n.d.
	PF	30	34.2±1.94	444.64±11.98	2049.5±696.5	44.4±9.1
Kenaf/flax (50/50)	PF	15	22.08±2.02	294.70±39.15	1488.5±792.5	29.3±5.3
	PF	30	22.85±2.30	256.44±45.71	5877.5±884.5	50.3±13.1
Hemp/flax (50/50)	PF	15	15.93±0.98	175.98±8.37	1420±518.5	20.4±7.4
	PF	30	12.83±1.81	174.99±14.25	5524±601	67.1±7.3
Wood/flax (75/25)	PF	15	17.86±2.27	237.80±54.57	n.d.	n.d.
	PF	30	17.14±1.61	219.25±24.95	1202±149	15.1±0.9
Typha		0	4.96±0.51	100.98±10.00	3100±92	21±2

All values in the table were obtained from panels of the same density (Wuzella et al., 2011)

Liu et al. (2013) developed cattail fibre reinforced polypropylene (PP) laminates and compared their mechanical properties (tensile, flexural) to those of jute/PP composites. In their findings, they noted that the mechanical properties of cattail/PP laminates were comparable with those of jute/PP composites. In addition to their first findings, they also noted that mechanical properties of a hybridised cattail/jute reinforced PP laminates with a fibre volume of 20/35/45 were better than those of the other two composites.

Rezig et al., (2015) investigated the flexural properties of cattail fibre reinforced polyester composites fabricated by hand lay-up technique. Composites were fabricated from randomly oriented cattail fibres in polyester resin and a non-woven cattail leaf fibre structure with various fibre weight fractions (7.3%, 10.3% and 12.6%). Results revealed better mechanical properties for composites fabricated from randomly oriented cattail leaf fibres reinforcements treated by alkali (20g/L of NaOH) and combined treatment (sea water followed by NaOH) and polyester resin as compared to those treated with only sea water. Also, at 12.6% fibre weight fraction, optimum values of flexural strength and modulus of 69.8 MPa and 6.16 GPa respectively were reported. All these were associated with the thorough elimination of foreign materials and wax residues from the surface of the fibre, enhancing its interfacial bond with polyester resin.

Advantages of cattail plants (Sojda & Solberg, 1993)

- As compared to other resources like coal, oil, glass and peat which take thousands or millions of years to form, cattail plants are renewable resource (annual).
- Cattail plants can be recycled without adding heat and carbon dioxide to the environment.
- Since cattail plants grow in wetlands, they do not compete for land that could be used for farming and planting of trees.
- Cattail plants grow near sewage treatment plants and by so doing, use some of the pollutants as nutrients and thus cleaning some of the troublesome nitrogen and phosphorus from the sewage.

2.3.2 Sisal Composites

Frollini et al., (2013) researched on bio-composites based on poly (butylene succinate) (PBS) reinforced with different natural fibres (coconut, sugarcane bagasse, curaua and sisal). The researchers used the traditional thermo-pressed moulding technique to prepare the composites and later on tested some of the mechanical properties (impact, flexural strength). From their study, sisal and curaua fibres showed a huge potential to be used as reinforcement in PBS matrix (Figure 2.4). This was an indication that sisal fibres have better mechanical properties as compared to some of the natural fibres.

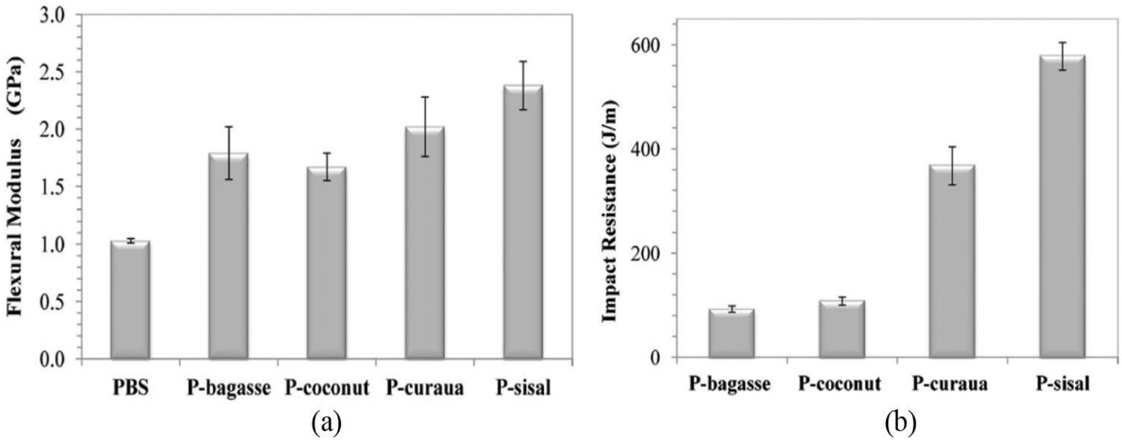


Figure 2.4: (a) Flexural modulus and (b) Impact resistance results of different fibre-reinforced polymer composites (Frollini et al., 2013)

Akash et al., (2016) studied the mechanical properties of NaOH treated sisal/coir fibre reinforced hybrid epoxy composites fabricated by cold pressing method. Results revealed better tensile and flexural strengths (53.13 MPa and 82.07 MPa respectively) with a 40 wt.% sisal/coir fibre weight fraction. Further, there was increase in water absorption and hardness values as the fibre weight fraction increased.

Romão et al., (2004) investigated the mechanical properties of a randomly oriented sisal fibre reinforced epoxy composite with varying alkali treatments. Their results revealed better tensile strength of 49.85 MPa at 4% w/v NaOH solution for 1 hour at room temperature as compared to 45.05 MPa for untreated fibres.

The influence of natural fillers like chopped banana and rice husks on the mechanical properties of glass polyester hybrid composite fabricated by hand lay-up technique were studied by Gupta et al., (2016). The study focused on the effect of 5%, 10% and 15% natural filler loadings on the mechanical behaviour of glass hybrid composites. The researchers concluded that hybridized glass fibre composites (with natural fillers) had better mechanical properties than glass reinforced composites.

Senthilkumar et al. (2016) investigated the effect of inter-laminar fibre orientation on tensile properties of sisal fibre reinforced polyester composites fabricated by cold pressing method. From their investigation, they reported that $0^0/90^0/0^0$ arrangements gave composites with highest strength as compared to the other types of combinations. Further, they found out that highest tensile modulus and strain resulted from $0^0/45^0/0^0$ oriented fibre composites.

Gupta et al., (2016) evaluated the mechanical properties of alkaline treated sisal/hemp fibre reinforced hybrid epoxy composite fabricated by simple compression moulding technique. The investigation revealed that more tensile and flexural strength resulted when 40 wt.% of sisal/hemp was used and increasing the weight percentage of fibre content increased the hardness strength of the composite.

Samuel et al., (2012) investigated the mechanical properties of fibres like ukam, banana, sisal, coconut, hemp and E-glass reinforced composites to evaluate their possibility for use as new materials for engineering applications. They found out that alkali treatment of ukam and sisal fibre greatly influenced their mechanical properties.

Mancinoa et al. (2018) evaluated the possibility of fabricating a high-performance biocomposite for structural applications using an eco-friendly partially bio-based epoxy and sisal fibres obtained by a proper optimization process. The study focused on sisal fibre optimization, where proper variety was selected. Fibres were obtained from ‘medium third’ of the sisal leaf and from leaves which were about 4 years old (age of the leaves). They fabricated three types of bio-composites using suitable manufacturing techniques viz; random short fibre bio-composite, random discontinuous fibre bio-composites and unidirectional long fibres bio-composites and investigated their mechanical properties. It was found that mechanical properties of unidirectional long fibres (ULF) bio-composites developed by preliminary manufacture of unidirectional 'stitched' fabrics were superior and therefore suitable for structural and semi-structural applications. This was supported by the experimental results, which showed the specific strength of ULF to be about 0.16kNm/g higher than that of steel (0.058-0.106kNm/g) or of aluminium alloys (0.15kNm/g), which are widely used for structural applications. The specific stiffness of about 11.1kNm/g was also obtained, certainly higher than that of ordinary fibre glass (6 kNm/g).

Idicula et al., (2005) investigated the mechanical properties of randomly oriented short banana/sisal hybrid fibre reinforced polyester composites. They prepared different layering patterns namely; bilayer (banana/sisal), tri-layer (banana/sisal/banana and sisal/banana/sisal), and intimate mixture composites by keeping a banana and sisal ratio of 1:1 and total fibre loading of 0.40 volume fraction. From their study, they found out that maximum stiffness resulted from composites where sisal is sandwiched between two layers of banana fibres. In addition, maximum damping properties were noted with a bilayer composite.

Wambua et. al., (2003) investigated the mechanical properties of different natural fibres (sisal, kenaf, hemp, jute and coir) reinforced polypropylene composites fabricated by compression moulding using a film stacking method with the aim of replacing glass in fibre-reinforced plastics. In this study, they found that the mechanical properties of the natural fibre reinforced composites investigated were compared favourably with the corresponding properties of glass mat polypropylene composites. Furthermore, increase in tensile strength and modulus were noted with increase in fibre volume fraction. The mechanical properties of sisal were comparable with that of other fibres.

Ramesh et al., (2013) undertook a comparative evaluation of the mechanical properties of hybrid glass fibre-sisal/jute reinforced epoxy composites prepared by hand lay-up process. Specimens from sisal/GFRP and jute/GFRP hybrid composites were then subjected to tensile and flexural tests where it was shown that sisal/GFRP composites possessed good tensile strength of up to 68.55MPa and jute/GFRP composites holds a maximum flexural load of 1.03kN which was slightly higher than the sisal/GFRP composites However, the performance of these natural fibre/GFRP hybrid composites is lower than that of GFRP composites and can be used in applications where medium strength is required.

Joseph et al., (2003) studied the mechanical properties of treated and untreated short sisal fibres reinforced polypropylene composites processed by melt mixing manufacturing technique. They found that addition of sisal fibres to pure PP increased the storage modulus (E1) and loss modulus (E11) due to the fact that the reinforcement imparted by the fibres allows stress transfer from the matrix to the fibre. A fibre length of 2 mm was found to be necessary for maximum dynamic modulus and loss modulus. Additionally, activation energy (E) and storage modulus (E1) of the chemically treated composites were found to be higher than those of untreated composites due to the improved fibre-matrix bond.

Bichang'a et al., (2017) investigated the effect of alkali treatment on the mechanical properties of a woven sisal fabric reinforced epoxy composite developed by hand lay-up method. Composites were fabricated with a 40% fibre weight fraction and allowed to cure at room temperature for 24 hours at a pressure of 3.3 kN/m^2. From their study, alkali treatment of the sisal woven fabric (in a 4% w/v NaOH solution for 1 hour at room temperature) was found to improve the mechanical properties of the resultant composite.

Venkateshwaran et al., (2011) investigated the mechanical and water absorption performance of a hybrid composite reinforced with banana and sisal fibres. They developed a banana epoxy composite using hand lay-up technique with various fibre lengths (5, 10, 15 and 20 mm) and fibre weight fractions (8,12,16 and 20%). In addition, they added sisal fibres at different weight fractions (25, 50 and 75%) to improve the mechanical properties of the resultant composites. From their investigation, better tensile, flexural and impact strength of 16.12 MPa, 57.53 MPa and 13.25 kJ/m^2 respectively at an optimal fibre length of 15 mm and fibre weight fraction of 16% for banana epoxy composite were reported. Furthermore, hybridization of banana with sisal in epoxy-based composites resulted in an increase of 16%, 4% and 35% in the tensile, flexural and impact strengths respectively.

Rizal et al. (2019) investigated the properties of polymer composites reinforced with cattail fibres treated with 5% w/v NaOH solution for 1, 2, 4 and 8 hours. The results showed that mechanical properties and crystallinity index of cattail fibres increased with processing time and that the fibres were suitable for composite fabrication.

2.4 Composite Manufacturing Methods

Different composite fabrication methods are available, each with a distinct characteristic and suitability for various uses. Examples of these fabrication techniques are hand lay-up, pultrusion, filament winding, vacuum bagging, resin transfer, infusion process, prepreg moulding and spray lay-up among others.

2.4.1 Hand Lay-up Method

This method is the most elementary composite manufacturing technique that is usually used. It is characterized by minimum investment capital requirement, low production volumes, labour intensiveness, flexible (components of different shapes can be produced), minimum infrastructural requirements and production of one moulded face

(Bichang'a et al., 2017; Ondiek et al., 2018). This composite manufacturing method is best suited for manufacture of large components such as wind turbines, marine crafts and boats. The manufacturing process involves: (1) placing/pouring impregnated reinforcements onto an open female die cavity; (2) spreading the impregnated reinforcements uniformly in the mould to build up and attain uniform thickness and; (3) closing the mould with the male die and applying pressure (and left to cure at room temperature). The main merits and demerits of hand lay-up method are listed below:

Merits of hand lay-up method:

- Flexible (components of different shapes can be produced)
- Production of large complex items
- Requires minimum investment in terms of capital and infrastructure
- Applicable in sandwich constructions
- Requires semi-skilled labour.

Demerits of hand lay-up method:

- Production of one moulded face
- It is a time consuming and labour-intensive process
- Requires low viscosity resins
- Low production volumes and high waste factor
- Limited reproduce-ability (operator dependence)

2.5 Research Gap

Based on the literature reviewed, limited studies have been done on the following areas:

i. Hybridization of cattail fibres with sisal fibres to form a polyester hybrid composite.

ii. Using manually extracted cattail fibres (decorticated fibres) in cattail fibre reinforced composite fabrication.

iii. Determination of mechanical and thermal properties of sisal/cattail hybrid polyester composites.

From studies done on cattail reinforced composites, it was found that cattail insulations cannot be marketed as low-cost products as compared to mineral insulating materials and therefore recommendation is made for the production of cattail insulation composites with additional value in order to compensate for the high price. This is the reason of hybridising cattail fibres with sisal fibres to come up with a resultant hybrid composite with better mechanical and low thermal conductivity properties which can be used as insulating components. The hybridising of cattail fibres with other natural fibres was also supported by Bajwa et al., (2015) and Liu et al., (2013). From their research, they found that superior mechanical properties were recorded when cattail fibres were blended with other fibres to form hybrid composites. Based on these research gaps, the current research intends to fabricate and determine mechanical (tensile, compressive, impact and flexural) and thermal conductivity properties of sisal/cattail fibre-reinforced hybrid composites and thus making some contribution to the existing literature on natural fibre-reinforced composites.

CHAPTER THREE: METHODOLOGY

3.1 Introduction

In this chapter, fabrication of the hybrid composites, the experimental design used, characterization and analysis of the hybrid composites are described. Figure 3.1 shows the methodological process followed in achieving the objectives of this study.

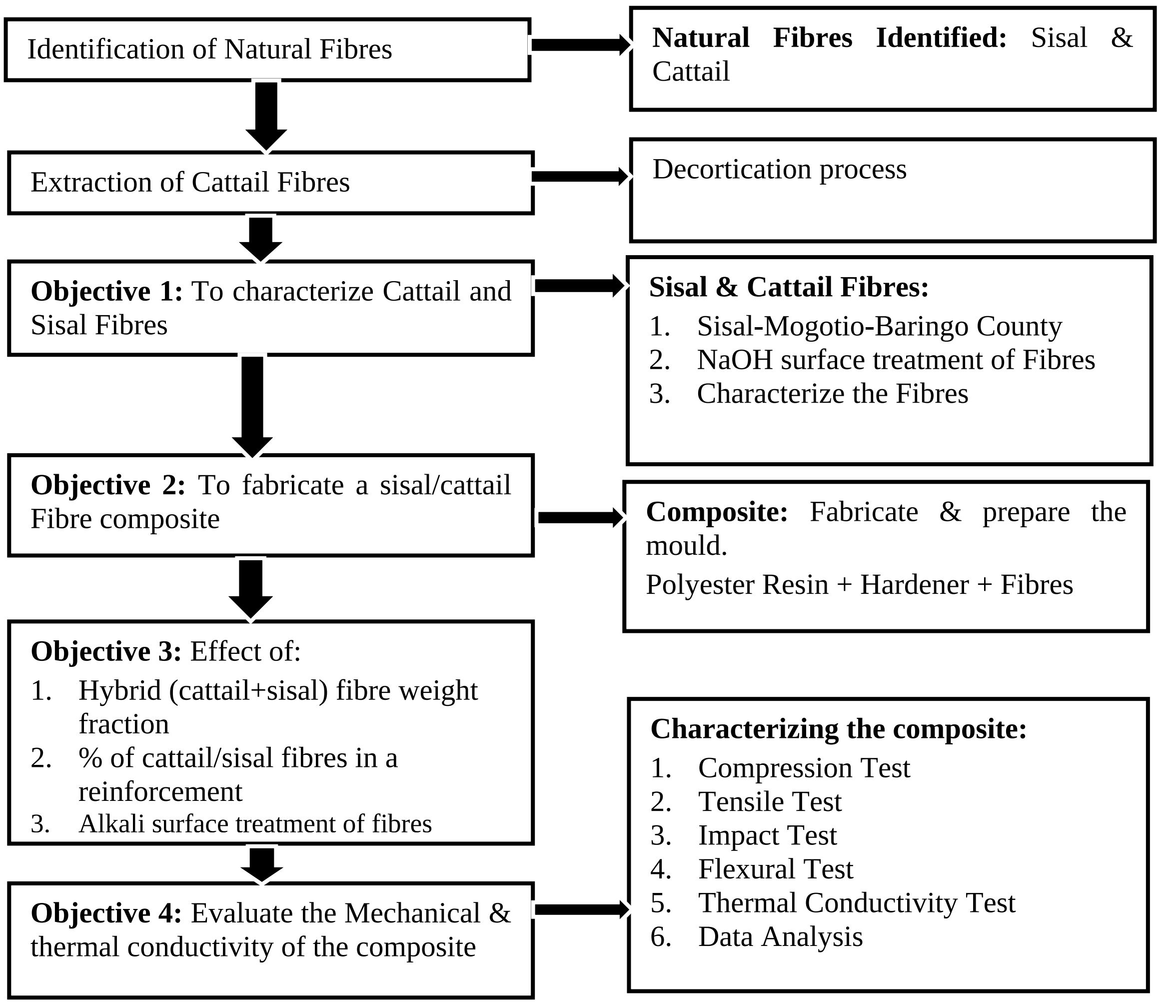


Figure 3.1: Methodological process in relation to the research objectives

3.2 Materials

The main materials used in this research are given in Table 3.1.

Table 3.1: Materials used in cattail/sisal fibre reinforced polyester composite fabrication

S/No.	Material and its Specifications
i.	Cattail fibres
ii.	Sisal fibres
iii.	Unsaturated Polyester resin (GP 1778)
iv.	Hardener (Methyl Ethyl Ketone Peroxide)
v.	Mould Release Agent (MR-8)
vi.	Thin Aluminium foil
vii.	Sodium hydroxide (NaOH)
viii.	Distilled water
ix.	Digital PH meter
x.	Acetone
xi.	Acetic acid

3.2.1 Cattail /Sisal Fibres

Sisal fibres were sourced from Lomolo Sisal Estate Ltd, Baringo County, Kenya while green mature cattail plant leaves were obtained from *Typha angustifolia* (cattail) plants wildly growing in a swamp near Moi University staff quarters, Eldoret, Kenya. Cattail leaves were separated from the stalk grouping at the base. Thereafter, the fibres were extracted from the leaves by decortication (Figure 3.2) while they were still green and then left to dry under the shed for five days.

Figure 3.2: Cattail fibre preparation (a) extraction process, (b) already extracted, and (c) drying of extracted fibres

3.2.2 Unsaturated Polyester Resin (UPR) and Hardener (Methyl Ethyl Ketone Peroxide)

Polyester resin, commercial code GP 1778 and methyl ethyl ketone peroxide (MEKP) hardener (Figure 3.3) were sourced from Henkel Chemicals (E.A.) Ltd, Industrial Area, Nairobi-Kenya. The resin and hardener (MEKP) were mixed thoroughly in a ratio of 1: 0.02 by weight (2% of the resin quantity) as per the manufacturer's recommendations. The matrix cures at room temperature for about 20-30 minutes. The properties of UPR are as presented in Table 3.2.

Table 3.2: Mechanical Properties of Unsaturated Polyester Resin-GP 1778

Properties	**Value**
Density	1.232g/cm^3
Tensile Strength	29.2Mpa
Tensile Modulus	2194.7Mpa
Flexural strength	70Mpa
Impact strength	9kJ/m^2
Elongation at break	4.2%

Figure 3.3: Precursor for synthesis of sisal/cattail hybrid composites: Mould release agent, Polyester resin, Acetone and Hardener (MEKP)

3.2.3 Mould Release Agent (MR8)

The mould release agent was sourced from Henkel Chemicals (E.A.) Ltd, Industrial Area, Nairobi-Kenya. It was used to prevent the resultant composites from sticking to the mould surface. The effect of MR8 on the mechanical and thermal conductivity properties of the resultant composites (if any) were not considered in this work.

3.2.4 Sodium Hydroxide

Sodium hydroxide (NaOH) was provided by Moi University Textile Laboratory. Sodium hydroxide was used for treating some sisal and cattail fibres, since some hybrid composites were to be fabricated using alkali treated fibre reinforcements. The use of sodium hydroxide was intended to remove cementing materials such as lignin, fats and other soluble impurities from the surface of the fibres and thus enhancing fibre-matrix bond in the resultant composites.

3.2.5 Acetone

Acetone was purchased from Henkel Chemicals (E.A.) Ltd, Industrial Area, Nairobi-Kenya (Figure 3.3). The main purpose of acetone in this work was to clean the mould and the mixing containers before and after each composite fabrication process.

3.2.6 Acetic acid

Acetic acid was used to neutralize the excess alkali in the fibres (sisal/cattail) after treatment. The acid was provided by Moi University Textile Laboratory where the fabrication work was done.

3.3 Fibre Surface Treatment (Cattail & Sisal)

To achieve objective two and three of the study, sisal and cattail fibres were treated with sodium hydroxide (NaOH) and characterized. Natural fibres have limitations in composite manufacturing due to their relatively high moisture sorption and poor compatibility with the matrix, therefore chemical treatments were considered to enhance the fibre-matrix bond by modifying their surfaces. These negative characteristics are exhibited in most natural fibres because they are comprised of cellulose, hemicellulose, lignin, pectin, waxes and water-soluble substances. Therefore, sisal fibres modification in this work was achieved by subjecting the fibres to a 4% w/v sodium hydroxide (NaOH) at room temperature for 1 hour (Bichang'a et al., 2017) (Figure 3.4). Further, cattail fibres were treated with 5% w/v sodium hydroxide at room temperature for 1 hour according to Dedeepya et. al., (2012) and Rizal et al., (2019) (Figure 3.4). After treatment, the fibres (sisal and cattail) were rinsed thoroughly with distilled water containing few drops of acetic acid to remove dissolved substances. Incorporation of acetic acid (1%w/v) when rinsing both treated sisal and cattail fibres was to neutralize excess sodium hydroxide in the fibres (observed using a digital PH meter; model check-mite PH-15). The rinsed fibres were then dried under the shade for five hours (Figure 3.5).

Figure 3.4: Alkali treatment of (a) Sisal and (b) Cattail fibres

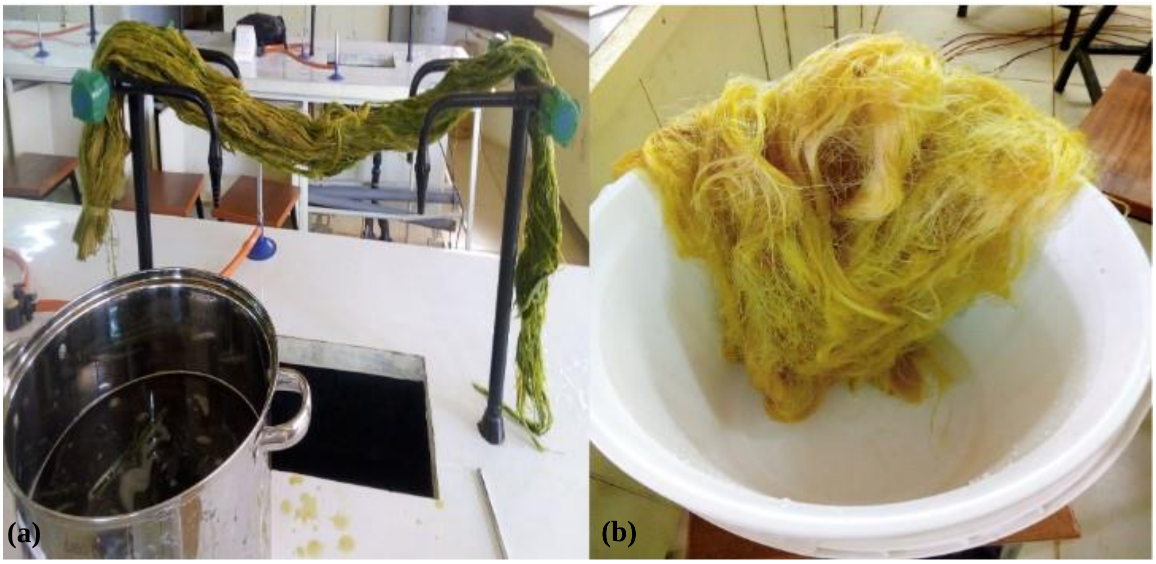


Figure 3.5: Rinsed (a) Cattail and (b) Sisal fibres (turned yellowish in colour)

3.4 Characterization of Sisal and Cattail Fibres

Both treated and untreated cattail and sisal fibres were characterized by determining their linear density and tensile properties. All tests were performed at 21.0 ± 2.0^{0}C and 65 ± 2% relative humidity.

3.4.1 Linear Density

Linear density of both sisal and cattail fibres was determined as per ASTM D1577-2018 by weighing known lengths of fibres using weighing machine Model ADAM PGW 453e. Thirty fibres, each from treated and untreated cattail and sisal fibres were picked randomly and then cut to a length of 300 mm as per the universal tensile testing machine gauge length to form four bundles of fibre. Each of these four test specimen bundles were weighed. From the measured fibre weight and number of fibre specimen in each bundle, weight of each fibre in the four bundles was determined. Therefore, with this weight in grams, linear density in tex was determined by dividing the fibre weight by its length in kilometres.

3.4.2 Tensile Strength

Tensile strength of both sisal and cattail fibres was determined as per ASTM D3822M-2014 using a universal tensile testing machine (Model TH2730; S/N:04-774-2008) (Figure 3.6) at a gauge length of 300 mm and speed of 5 mm/min. Tensile strength was determined for the four test specimen bundles of fibres (each from treated and untreated sisal and cattail fibres) by taking an average of 30 tests replicates for each. From these tests, fibre tensile strength in terms of breaking tenacity (cN/tex) was determined by dividing the breaking force (cN) by the linear density (tex) of the respective fibres (treated and untreated cattail and sisal fibres). Also, assuming the fibres to be of cylindrical nature and diameters to be similar to those reported in literature, tensile strengths were calculated from first principles and given in MPa.

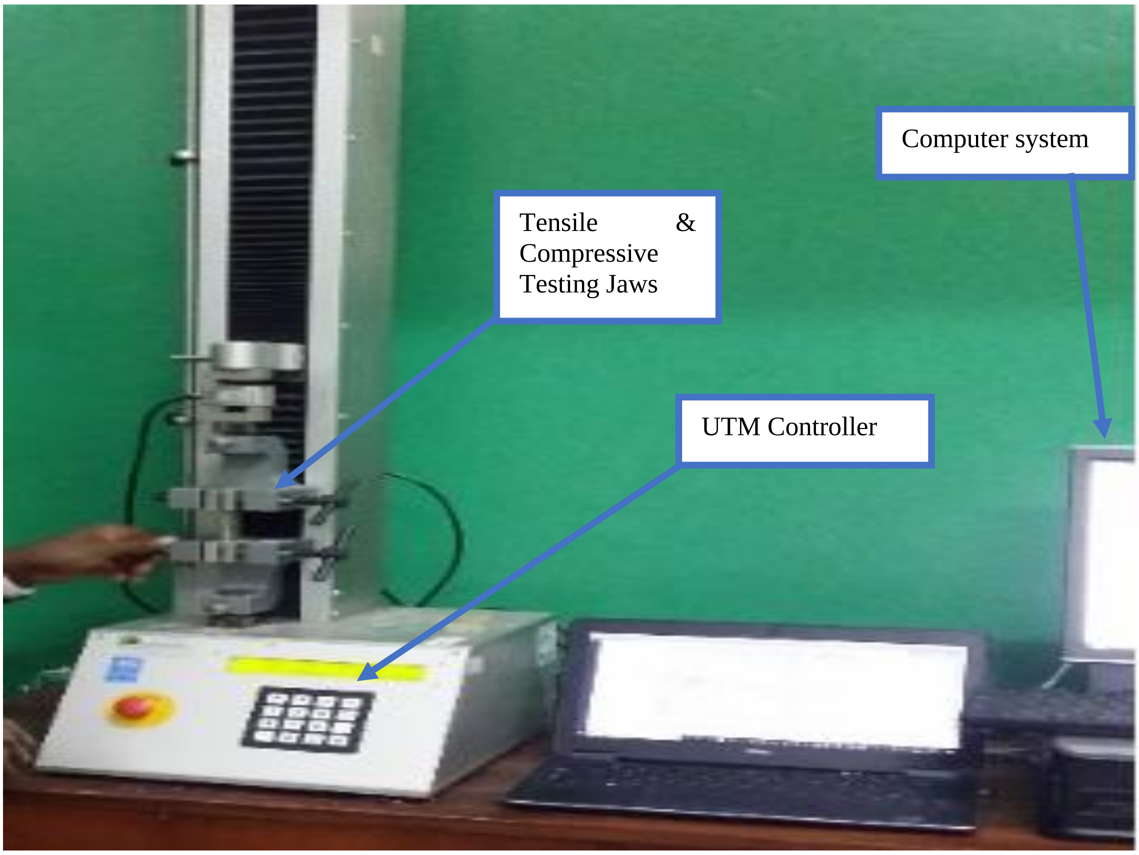


Figure 3.6: Universal Testing Machine (MIT Dept. Moi University)

3.5 Fibre Preparation

3.5.1 Cattail Fibre Preparation

Mechanically extracted dry cattail fibres (treated and untreated) were cut to a length of 15 mm and then stored in polythene paper bags.

3.5.2 Sisal Fibre Preparation

Sisal fibres as obtained from the source were cleaned with warm distilled water (for untreated) to remove some of the soluble impurities, after which they were dried under the shed for five hours. These fibres (treated and untreated) were then cut to a length of 15 mm and stored in polythene paper bags.

3.5.3 Oven Pre-drying

Sisal and cattail fibres (already cut to a length of 15 mm) were then pre-dried in an oven for one hour at 80^{0}C. This was to further assist in removal of excess moisture from the fibres that might lead to poor fibre-matrix adhesion.

3.6 Mould Making

A female die cavity of internal dimensions measuring 310 mm × 310 mm × 25 mm with its male die counterpart (lid) measuring 300 mm × 300 mm × 5 mm with sufficient stiffness were fabricated at the School of Engineering Workshop, Moi University- using a well-polished iron metal sheet (Figure 3.7).

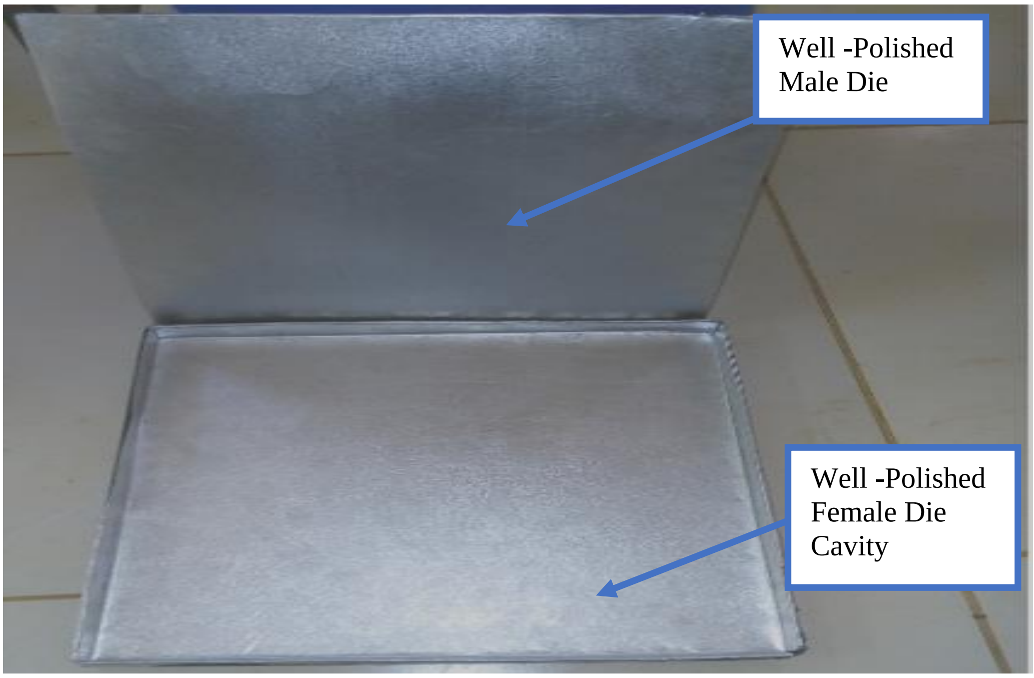


Figure 3.7: Female die cavity with its male counterpart used in composite fabrications

3.7 Experimental Design

In this research, experimental test runs with two dependent variables namely hybrid (cattail + sisal) fibre weight fraction (X_1) and percentage of sisal/cattail fibres in the hybrid (X_2) were carried out using an experimental design below with five levels coded by -1, -0.5, 0, +0.5 and +1.

Table 3.3: Relationship between parameters and levels for the sisal/cattail polyester composites

Parameters	**Levels**				
	Lowest Coded as -1	Low Coded as -0.5	Centre Coded as 0	High Coded as +0.5	Highest Coded as +1
Hybrid (Sisal + Cattail) Fibre Weight Fraction (wt.%) X_1	5	10	15	20	25
% of Sisal/Cattail Fibres in the Hybrid (X_2)	0	25	50	75	100

The hybrid (Cattail + Sisal) fibre weight fraction (wt.%) used in this study were varied between 5% and 25% (Vimalanathan et al., 2016) and within each of this fibre weight fraction (wt.%), the proportions between cattail and sisal fibres were varied as below;

i. 100% cattail fibre and 0% sisal fibre.
ii. 75% cattail fibre and 25% sisal fibre.
iii. 50% cattail fibre and 50% sisal fibre.
iv. 25% cattail fibre and 75% sisal fibre.
v. 0% cattail fibre and 100% sisal fibre.

These mixing ratio variations between cattail and sisal fibres are to show the effect of hybridization in the resultant composite. From Table 3.4 and 3.5, a total of ten cattail/sisal fibre reinforced polyester hybrid composites were fabricated.

Table 3.4: Effect of varying the hybrid (cattail + sisal) fibre weight fraction, wt.% (X_1) for response variables (Coded values)

Test No.	**Coded Values**	
	X_1	**X_2**
1	-1	0
2	-0.5	0
3	0	0
4	+0.5	0
5	+1	0

Table 3.5: Effect of varying the percentage of sisal/cattail fibres in the hybrid (X_2) for response variables, % (Coded values)

Test No.	**Coded Values**	
	X_1	**X_2**
1	0	-1
2	0	-0.5
3	0	0
4	0	+0.5
5	0	+1

Table 3.6: Effect of varying the hybrid (cattail + sisal) fibre weight fraction (X_1) for response variables (Physical values)

Test No.	**Physical Values**	
	X_1	**X_2**
1	5	50/50
2	10	50/50
3	15	50/50
4	20	50/50
5	25	50/50

Table 3.7: Effect of varying the percentage of sisal/cattail fibres in the hybrid (X_2) for response variables (Physical values)

Test No.	**Physical Values**	
	X_1	**X_2**
1	15	0/100
2	15	25/75
3	15	50/50
4	15	75/25
5	15	100/0

3.8 Composite Fabrication

Cattail/sisal fibre reinforced hybrid composites were fabricated by hand lay-up technique. Firstly, untreated test samples were fabricated with different hybrid fibre weight fractions (X_1) at a 50/50 sisal/cattail fibres in the hybrid. Secondly, test samples were fabricated with different percentages of sisal/cattail fibres in the hybrid (X_2) at a constant hybrid fibre weight fraction and lastly, a treated test sample was fabricated using treated sisal and cattail fibres at a constant hybrid fibre weight fraction (15wt.%) and percentage of sisal/cattail (50/50) fibres in the hybrid. Varying hybrid fibre weight fraction (X_1) and percentages of sisal/cattail fibres in the hybrid (X_2) was to investigate their effect on tensile, compression, flexural, impact and thermal conductivity properties. Further, cattail/sisal fibres treatment was to establish the effect of alkali (NaOH) treatment on the mechanical and thermal conductivity properties of the resultant composite.

Fabrication conditions for all the test samples were kept constant as the following experimental procedure was followed:

a) Both female die cavity and its corresponding male die were thoroughly cleaned with acetone, followed with the application of mould release agent (MR8) on the inner surfaces (Figure 3.8) and then left to dry.

b) The inner surfaces of the mould already sprayed with mould release agent (MR8) were then covered with aluminium foil (Figure 3.8). Aluminium foil was meant to prevent the composite from sticking onto the mould surfaces and further ensure good surface finish.

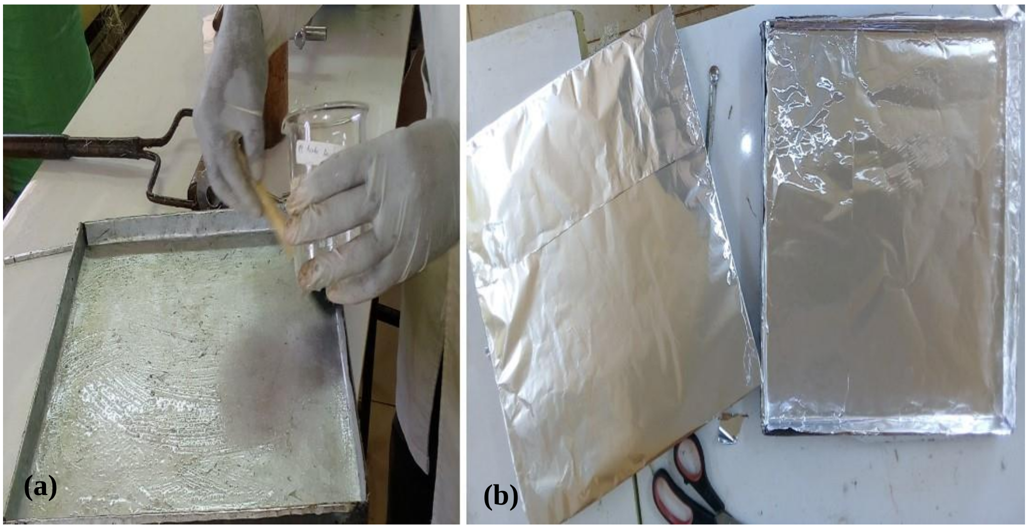


Figure 3.8: (a) Application of MR8 (b) Moulds covered with aluminium foil

c) Cattail and sisal fibres were weighed on a digital electronic weighing machine (Model: Mettler Toledo with a capacity of 2100g and a sensitivity of 0.001g) based on their percentages in the hybrid for each experimental set-up and then thoroughly mixed in a bowl (Figure 3.9). Based on the measured mass of cattail/sisal fibres and desired hybrid weight fraction, the corresponding polyester resin and hardener mass were computed.

d) Unsaturated polyester resin (UPR) and hardener (MEKP) were mixed in the ratio 1: 0.02 by weight as per manufacturer's instructions and stirred thoroughly but gently to make the matrix (Figure 3.9).

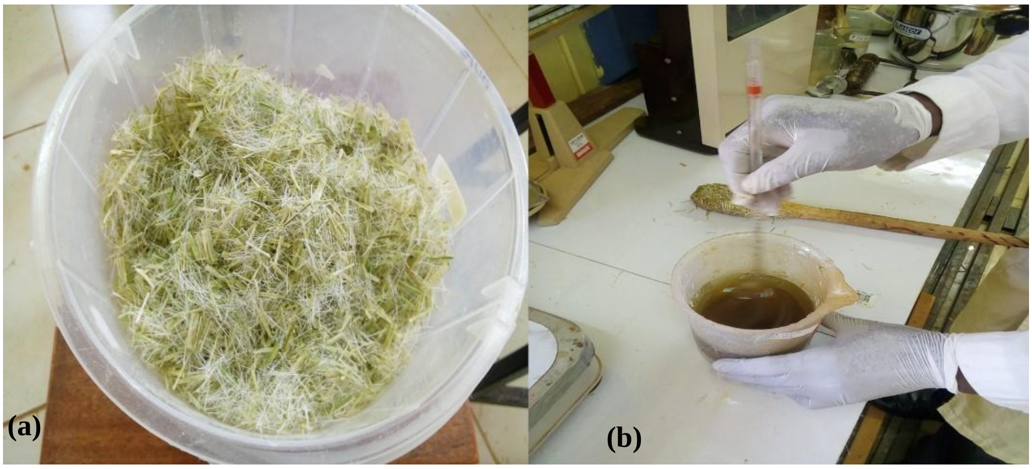


Figure 3.9: (a) Mixed cattail and sisal fibres (b) Mixing UPR and Hardener (MEKP)

e) The matrix was then poured into the jar containing the mixture of cattail and sisal fibres (prepared in (c) above) and then stirred gently and thoroughly for about 10-15 minutes to ensure uniform dispersion of fibres within the matrix and full impregnation with the matrix (Figure 3.10).

f) The content was then poured into the female die cavity with the help of the stirring rod and then spread gently to ensure uniform thickness of the resultant composite (Figure 3.10).

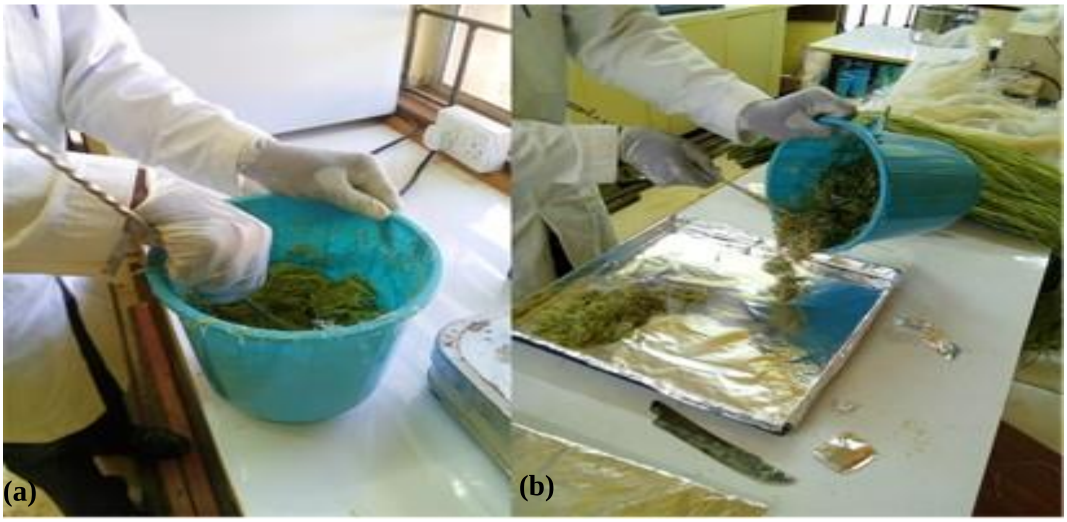


Figure 3.10: Mixing of the matrix with sisal/cattail fibres and pouring the content into the female die cavity

g) Finally, the female die cavity was closed with a male die and allowed to cure at ambient conditions for 6 hours at a pressure of 3.27 kN/m^2. This was to ensure uniform consolidation of the mixture and therefore minimise the number of defects in the resultant composite.

h) After 6 hours, the mould was opened to remove the resultant moulded composite.

i) To get the required number of samples, procedure (a)-(h) was repeated.

j) Various specimens were then cut from the fabricated hybrid composites to conform to various ASTM standards' dimensions using a hack saw.

3.9 Mechanical & Thermal Properties of the Resultant Composites

The resultant hybrid composite samples were prepared in accordance with the testing standards used (i.e. ASTM and ISO standards). Cut specimen samples for flexural and impact tests were conditioned at a relative humidity of 65% and ambient temperature of 23±2°C for 48 hours in the Materials Engineering Laboratory of Multimedia University Nairobi, Kenya before testing them using a universal testing machine (Model UT-10; S/No: 2015/12) (Figure 3.11). and a Charpy impact testing machine (model HLE; S/No:2015/15) respectively. Further, tensile and compression tests were carried out at Rivatex East Africa Limited textile laboratory using a universal testing machine (Type TH2370; S/N:04-774-2008) (Figure 3.6). The specimens were conditioned in the same laboratory for 48 hours at a temperature of 23 $\pm 2^0$C and relative humidity of 65% prior to performing the tests.

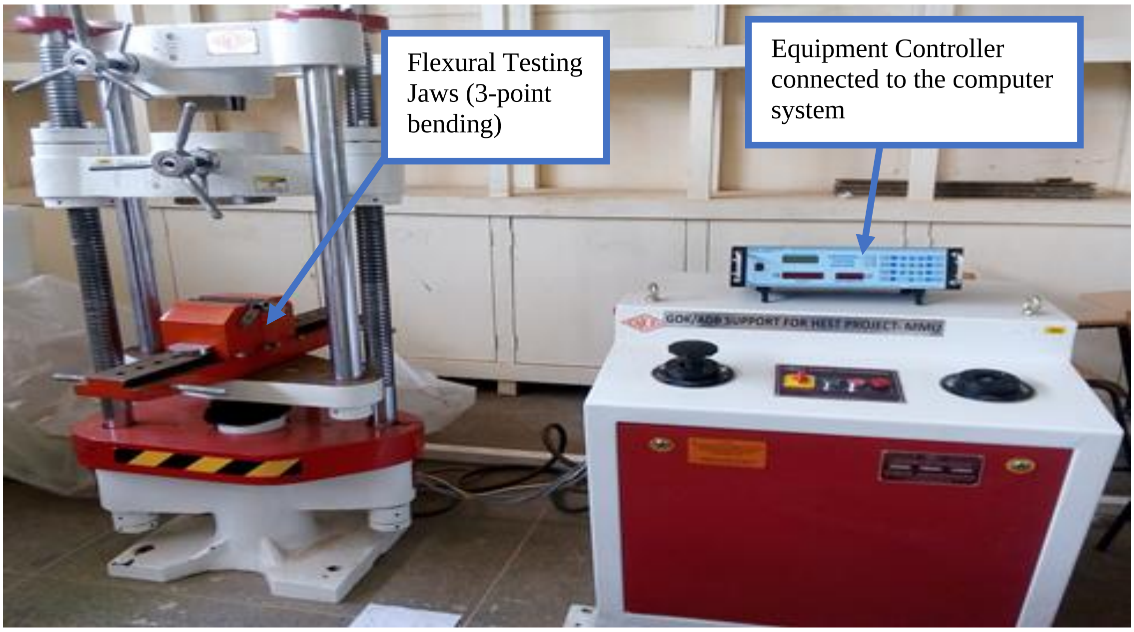


Figure 3.11: Universal Testing Machine (Multimedia University-Kenya)

Thermal conductivity tests were on the other hand carried out using a thermal conductivity apparatus (S/No: P5687/326) (Figure 3.12) in the Thermodynamic Engineering Laboratory of Jomo Kenyatta University of Technology (JKUAT), Nairobi, Kenya in accordance with ASTM C518-1998.

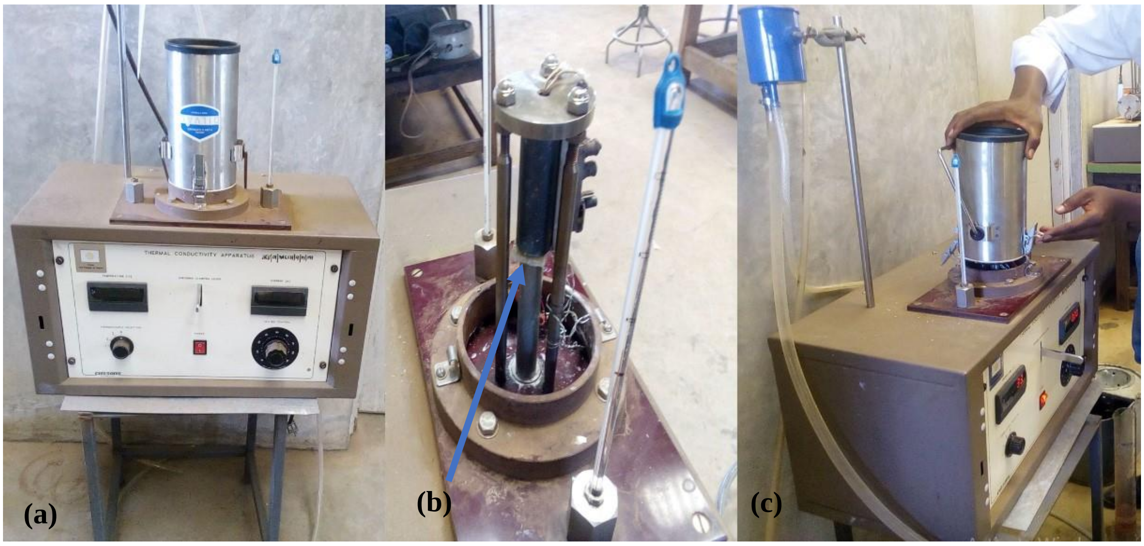


Figure 3.12: (a) Thermal conductivity apparatus, (b) Specimen positioning and (c) Closing with Dewar insulator

3.9.1 Tensile Testing

The samples for tensile testing were cut to the required dimensions using a hack saw, a file and sand paper. The sample preparation in terms of dimensions, gauge, length and speed were performed according to the ASTM D638-2014 standard. The tests were performed using a Universal Testing machine equipped with a 5 kN load cell and a cross head speed of 2 mm/min (Figure 3.6). For each experimental run, 10 specimen pieces were tested out of which, five best and consistent specimens with minimal variances were tabulated. The tensile strengths of the specimen composites were calculated by dividing the maximum load in Newtons by the original cross-sectional area of the specimen in square metres (Eqn.1).

$$\text{Tensile Strength (MPa)} = \frac{\text{Maximum Tensile Load}}{\text{Original Cross−Sectional Area}} \rightarrow \frac{\mathrm{P_{Max}}}{\mathrm{A}} \qquad \text{(Eqn.1)}$$

The modulus of elasticity of the cattail/sisal hybrid composite was computed by extending the initial linear portion of the load-extension curve and dividing the difference in stress corresponding to any segment of section of this straight line by the corresponding difference in strain.

3.9.2 Compression Testing

Compression testing of the resultant composite samples was done as per ASTM D3410M-2003 standard at a cross head speed of 5 mm/min with a load of 5 kN (Figure 3.6). For each experimental run, 10 specimen samples were tested, out of which, the mean values of five best and consistent specimens with minimal variances were tabulated. Maximum compressive loads that were carried by the specimen were recorded. The compressive strength of the resultant composite was calculated by dividing the maximum composite load by the original minimum cross-sectional area of the specimens (Eqn. 2).

$$\text{Compressive Strength } (\sigma_{FC}) = \frac{\text{Maximum Compressive Load}}{\text{Original Cross−Sectional Area}} \rightarrow \frac{\rho_{Max}}{\mathrm{A}} \qquad \text{(Eqn.2)}$$

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

3.9.3 Flexural Testing

Flexural tests of the resultant cattail/sisal composites were carried out in accordance with ASTM D790-2003 standard. The test procedure involved here was the application of a 3-point flexure loading system, where a load was applied at the middle of a specimen sample supported at two points using a UTM (Figure 3.11). The testing machine was computer controlled with a load cell of 5 kN at a cross speed of 2 mm/min. As per this standard, the variation of the distance between the supports (span length), width and overall length of the specimens to be tested were computed as follows;

- Span Length (L): 16 times specimen thickness (to the nearest whole number)
- Specimen width (b): ¼ times span length (to the nearest whole number).
- Overall Length: 25 mm overhanging allowance on both sides plus individual span length.

For each experimental run, 10 specimen samples were tested, out of which, the mean values of five best and consistent specimens with minimal variances were tabulated. The flexural strength of the cattail/sisal fibre reinforced composites were calculated for any point on the load-deflection curve (Eqn. 3).

$$\text{Flexural Strength } (\sigma_f) = \frac{3P_{MaxL}}{2\text{bd}^2} \qquad \text{(Eqn.3)}$$

Where P_{Max} is the maximum load (N), L is the span length (mm), d is the thickness (mm), b is the width (mm) and σ_f is flexural strength (MPa).

3.9.4 Impact Testing

The test samples were prepared as per the ISO 179-1:2000 standard. The tests were done using a Charpy Impact Tester (Model: HLE & S. No: 2015/15). For each experimental run, 10 specimen samples were tested, out of which, the mean values of five best and consistent specimens with minimal variances of the absorbed energy to break were recorded and used to determine the impact strength of the composite (Eqn. 4).

$$\text{Charpy Impact Strength of Unnotched Specimen}(a_{CU}) = \frac{E}{h.b} \times 10^3 \qquad \text{(Eqn.4)}$$

Where a_{CU} is the Charpy impact strength of unnotched specimen (kJ/m^2), h is the thickness (mm), b is the width (mm) and E is the energy absorbed (J) by breaking the specimens.

3.9.5 Thermal Conductivity Testing

Thermal conductivity (λ) of the resultant composite samples was conducted as per ASTM C518-1998 standard by using a thermal conductivity apparatus (Figure 3.12). The thermal conductivity of cattail/sisal reinforced composite samples was established by a steady state one dimensional heat flux through a test specimen measuring 25 mm × 25 mm taken between two parallel plates (hot and cold) at constant but different temperatures (T_1-T_4). The temperature (T_1-T_4) was varied between 40-120^{0}C at intervals of 40^{0}C and ensuring that, at each stabilized temperature, the other thermocouple (cold side) is reading a constant temperature.

Since one test specimen was sandwiched between two thermocouples, thermal conductivity was determined by using the following equations (Eqn. 5-7). From each specimen, four readings were taken from temperature (T_1-T_4), out of which, the mean values of three best and consistent thermal conductivity values with minimal variances were recorded and used to determine the thermal conductivity of the composite.

$$\text{Heat supplied (Q)} = J \times \frac{M(W_1 - W_2)}{t}\ [W] \qquad \text{(Eqn.5)}$$

Where Q is the heat supplied to the calorimeter from the heater (watts), J is the conversion factor of heat (4136 J/Kcal), M is the mass of water collected (Kg), W_1 is the water inlet temperature (^{0}C), W_2 is the water outlet temperature (^{0}C) and t is the time to collect M Kg of water (sec).

Quantity of Heat passing through a Unit Area $(q) = \frac{Q}{A}\ [W/_{m^2}]$ (Eqn.6)

Where q is the quantity of heat passing through a unit area of the sample in a unit time (W/m^2) and A is the cross-sectional area of the specimen (m^2)

Thermal Conductivity $(\lambda) = \frac{q \times d}{T_1 - T_2}\ [W/_{mK}]$ (Eqn.7)

Where q is the quantity of heat passing through a unit area of the sample in a unit time (W/m^2), d is the thickness of the specimen (m), T_1 is the thermocouple temperature (^{0}C) of heated surface of the sample and T_2 is the thermocouple temperature (^{0}C) of cold surface of the sample.

3.9.6 Fractography Study

Surface morphology for both treated and untreated fibres (sisal/cattail) together with their respective sisal/cattail polyester hybrid composites were investigated using MSX-500Di Scopeman Digital Microscope (Herter Instruments, Barcelona, Spain).

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Properties of Sisal and Cattail Fibre Reinforcements

Sisal and cattail fibres were characterized for tenacity (cN/tex) and linear density (tex).

4.1.1 Sisal Fibre

A higher linear density of 26.17 tex was recorded with untreated sisal fibres as compared to 10 tex of the alkali treated fibres (Table 4.3). This was attributed to the reduction of fibre diameter due to the loss of weight resulting from the removal of cementing materials (Gañan et al., 2005) such as lignin, fats and other impurities as shown in Figure 4.1a-b. Linear density for treated fibres obtained in this work was close to 7.83 tex treated fibres as reported by Mahato et al., (2014).

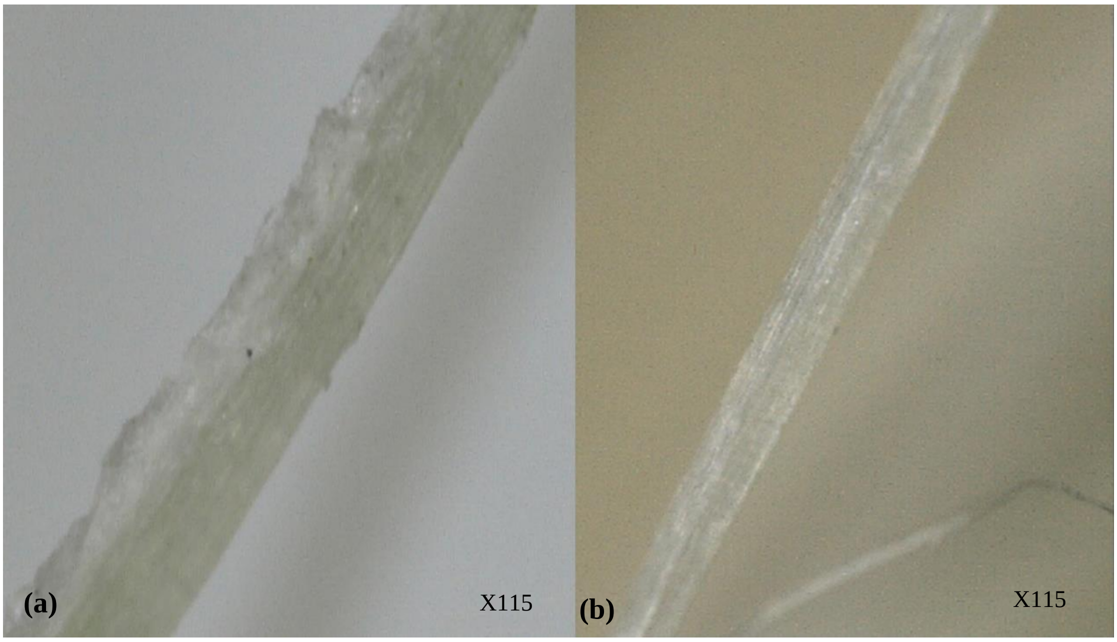


Figure 4.1: Micrograph for (a) Untreated sisal (b) treated sisal

Figure 4.1a-b shows optical images of treated and untreated sisal fibre bundles. The images confirm the reduction of sisal fibre diameter after subjecting the fibre to 4%w/v NaOH for one hour. This reduction could be possibly because of dissolution of alkali soluble materials such as wax, lignin, hemicellulose and other impurities during the alkali treatment exercise.

Tenacity of treated sisal fibres was 146.26 cN/tex (higher) as compared to 23.52 cN/tex of the untreated fibres (Table 4.3). High tenacity values of alkali treated sisal fibres can be attributed to the removal of lignin and other soluble impurities thereby increasing the aspect ratio and thus tenacity of the fibres (Mahato et al., 2014). Tenacity results on treated and untreated sisal fibres obtained in this research were analyzed using T-test statistical technique shown in Table 4.1 to ascertain their significance. The paired T-test analysis showed a higher calculated absolute t-value as compared to the two tailed t-critical value and therefore suggesting a significant difference between the tenacity of treated and untreated sisal fibres.

Table 4.1: Paired T-test analysis of untreated and treated sisal fibre tensile strength

Indexes	**Untreated**	**Treated**
	Value	Value
Mean	23.5234	146.2592
Variance	0.008645	0.655236
Observations	20	20
Pearson Correlation	0.250325	
Hypothesized Mean Difference	0	
df	19	
t Stat	**-6.93633**	
P (T<=t) one-tail	6.51E-07	
t Critical one-tail	1.729133	
P (T<=t) two-tail	1.3E-06	
t Critical two-tail	**2.093024**	

4.1.2 Cattail Fibre

Linear density of treated cattail fibres was found to be lower (12.33 tex) as compared to 35.17 tex for the untreated fibres (Table 4.3). According to Gañan et al., (2005), alkali treatment removes the cementing materials such as lignin on the surfaces of the fibres and thus reducing their diameter (Figure 4.2a-b). Sana et al., (2014) reported a comparable linear density of 32 tex for untreated cattail fibres and a linear density of between 10-30tex for alkali treated fibres.

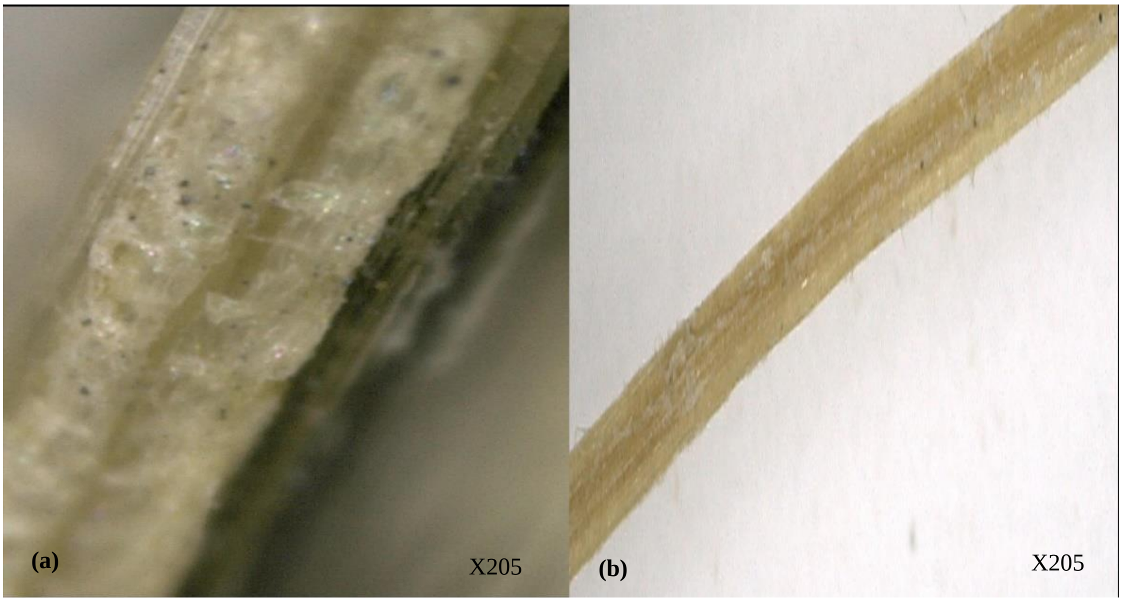


Figure 4.2: Micrograph of (a) Untreated cattail (b) Treated cattail fibres

Figure 4.2a-b shows optical images of treated and untreated cattail fibres. It is evident from the images that the diameter of the fibres decreased substantially upon alkali treatment. Reduction in diameter can be explained by the fact that amorphous fractions of fibres, such as lignin and also surface impurities were removed. Removal of these components from the fibres results to increase in aspect ratio as well as tenacity of the fibres.

Table 4.2 compares the values of tenacity for treated and untreated cattail fibres. The mean tenacity of treated cattail fibres was 35.35 cN/tex (higher) as compared to those of untreated fibres at 9.46 cN/tex (Table 4.3). It is also important to note that the calculated absolute t-value was higher than the two tailed t-critical value. This therefore suggests that there is a significant difference between the tenacity of treated and untreated cattail fibres. Further, *p*-value (two-tail) is less than 0.05 and therefore ascertaining the differences. Tenacity of treated cattail fibres reported in this study is comparable to

30.17±4.7 cN/tex reported by Mortazavi and Moghaddam (2010) while investigating the structure of cattail leaf fibres. Tenacity for treated cattail fibres were comparable with previous studies. For instance, Mortazavi and Moghadam (2009) studying cattail fibres, reported a tenacity of 34.87 cN/tex with 6% alkali treatment and 3% ethylene diamine tetra acetic acid (EDTA). Sana et al. (2014) researching on the structure of Tunisian *Typha* leaf fibres extracted using a NaOH hot bath, reported a tenacity of 7.76 cN/tex. Rezig et al. (2016) reported a tenacity of 12.41 cN/tex at optimized cattail fibre extraction process of 3 hours, 20g/L NaOH and 100^{0}C from cattail plant leaves.

Table 4.2: Paired T-test analysis of untreated and treated cattail fibre tensile strength

Indexes	**Untreated**	**Treated**
	Value	Value
Mean	9.4629	35.3459
Variance	0.003796	0.054828
Observations	20	20
Pearson Correlation	-0.03743	
Hypothesized Mean Difference	0	
Df	19	
t Stat	**-4.73725**	
P(T<=t) one-tail	7.17E-05	
t Critical one-tail	1.729133	
P(T<=t) two-tail	**0.000143**	
t Critical two-tail	**2.093024**	

Table 4.3: Physical and Mechanical properties of sisal and cattail fibres

Properties	**Cattail Fibre**	**Sisal Fibre**	**Reference (s)**
Diameter, Untreated, µm	520	205 ± 4.3	(Idicula, Joseph, & Thomas, 2010; Sana et al., 2014)
Diameter, Treated, µm	506	170	(Cyras, Vallo, Kenny, & Vázquez, 2004; Sana et al., 2014)
Linear Density Treated (tex)	12.33	10.00	This study
Linear Density Untreated (tex)	35.17	26.17	This study
Tenacity Treated (cN/tex)	35.35	146.26	This study
Tenacity Untreated (cN/tex)	9.46	23.52	This study
Tensile Strength Treated, MPa	16.46	498.87	This study
Tensile Strength Untreated, MPa	9.16	170.27	This study
Microfibrillar angle	-	20	(Idicula et al., 2010)
Lumen size	1.03µm	11mm	(Idicula et al., 2010) (Chakma et al., 2017)
Cellulose content (%)	53.47	65-68	(Sayed Majid Mortazavi & Moghadam, 2009; Naveen, Jawaid, Amuthakkannan, & Chandrasekar, 2019)

4.2 Mechanical and Thermal Conductivity Properties

Flexural, tensile, compressive, impact and thermal properties of sisal/cattail fibre-reinforced polyester hybrid composite were determined.

4.2.1 Flexural Properties of Sisal/Cattail Polyester Hybrid Composites

Table 4.4 summarizes the flexural properties of sisal/cattail hybrid composites with a constant fibre blend ratio of 50/50 (sisal/cattail) and varying hybrid fibre weight fraction from 5 to 25wt.%.

Table 4.4: Flexural properties of sisal/cattail hybrid polyester composite at 50/50 sisal/cattail in the hybrid

Hybrid Fibre Weight Fraction (wt.%)	Thickness, h (mm)	Span Length, L (mm)	Width, b (mm)	Max Load, N	Flexural Strength (MPa)	Flexural Modulus (GPa)
5	3.15	50	13	47.61	27.68(1.19)	2.09(0.19)
10	5.85	94	23	176.18	31.56(2.55)	3.04(0.18)
15	7.07	113	28	302.62	36.65(2.60)	3.83(0.14)
20	8.16	131	33	502.31	44.92 (4.37)	4.45(0.33)
25	9.74	156	39	600.67	37.99 (2.54)	3.85(0.10)

[a] Values in parentheses are standard deviations

Table 4.5 summarizes the flexural properties of sisal/cattail hybrid composites with a constant fibre weight fraction of 15wt.% and varying sisal to cattail blend ratio from 0% to 100%.

Table 4.5: Flexural properties of sisal/cattail hybrid polyester composite at 15wt.% hybrid fibre weight fraction

% of sisal / cattail in the hybrid	Thickness, h (mm)	Span Length, L (mm)	Width, b (mm)	Max Load, N	Flexural Strength (MPa)	Flexural Modulus (GPa)
0/100	7.75	124	31	207.42	20.72(1.76)	2.72(0.126)
25/75	5.74	92	23	134.59	23.65(1.35)	3.04(0.137)
50/50	7.07	113	28	288.83	34.98(4.8)	3.83(0.137)
75/25	7.72	124	31	456.62	45.97(4.29)	4.26(0.225)
100/0	8.08	129	32	341.50	31.63(4.3)	2.98(0.083)

[a] Values in parentheses are standard deviations

4.2.2 Tensile Properties of Sisal/Cattail Polyester Hybrid Composites

Table 4.6 summarizes the tensile properties of sisal/cattail hybrid composites with a constant fibre blend ratio of 50/50 (sisal/cattail) and varying hybrid fibre weight fraction from 5 to 25 wt.%.

Table 4.6: Tensile properties of sisal/cattail hybrid polyester composite at 50/50 sisal/cattail in the hybrid

Hybrid Fibre Weight Fraction (wt.%)	**Thickness, h (mm)**	**Cross-sectional Area (mm^2)**	**Maximum Load (N)**	**Tensile Strength (MPa)**	**Tensile Modulus (GPa)**
5	3.15	59.85	995.90	16.64(1.86)	1.37(0.065)
10	5.85	111.15	2692.05	24.22(2.44)	2.62(0.209)
15	7.07	134.33	3800.19	28.29(1.25)	3.47(0.233)
20	8.16	155.04	4868.26	31.40(0.23)	3.81(0.217)
25	9.74	185.06	4868.93	26.31(0.22)	2.5(0.124)

[a] Values in parentheses are standard deviations

Table 4.7 summarizes the tensile properties of sisal/cattail hybrid composites with a constant fibre weight fraction of 15wt.% and varying sisal to cattail blend ratio from 0% to 100%.

Table 4.7: Tensile properties of sisal/cattail hybrid polyester composite at 15wt.% hybrid fibre weight fraction

% of sisal and cattail in the hybrid	**Thickness, h (mm)**	**Cross-sectional Area (mm^2)**	**Maximum Load (N)**	**Tensile Strength (MPa)**	**Tensile Modulus (GPa)**
0/100	7.75	147.25	2718.24	18.46(0.98)	2.05(0.139)
25/75	5.74	109.06	2500.75	22.93(0.63)	2.57(0.166)
50/50	7.07	134.33	3800.75	28.29(1.25)	3.47(0.233)
75/25	7.72	146.68	4750.97	32.39(0.72)	3.82(0.108)
100/0	8.08	153.52	4247.89	27.67(1.43)	2.73(0.144)

[a] Values in parentheses are standard deviations

4.2.3 Compressive Properties of Sisal/Cattail Polyester Hybrid Composites

Table 4.8 summarizes the compressive properties of sisal/cattail hybrid composites with a constant fibre blend ratio of 50/50 (sisal/cattail) and varying hybrid fibre weight fraction from 5 to 25wt.%.

Table 4.8: Compressive properties of sisal/cattail hybrid polyester composite at 50/50 sisal/cattail in the hybrid

Hybrid Fibre Weight Fraction (wt.%)	**Thickness, h (mm)**	**Cross-sectional Area (mm^2)**	**Compressive Load (N)**	**Compressive Strength (MPa)**	**Compressive Modulus (GPa)**
5	3.15	78.75	1300.95	16.52(0.43)	0.99(0.109)
10	5.85	146.25	2746.58	18.78(0.25)	1.48(0.112)
15	7.07	176.75	3720.59	21.05(0.48)	2.26(0.155)
20	8.16	204	4893.96	23.99(0.16)	2.82(0.138)
25	9.74	243.5	4772.60	19.60(0.29)	2.46(0.236)

[a] Values in parentheses are standard deviations

Table 4.9 summarizes the compressive properties of sisal/cattail hybrid composites with a constant fibre weight fraction of 15wt.% and varying sisal to cattail blend ratio from 0% to 100%.

Table 4.9: Compressive properties of sisal/cattail hybrid polyester composite at 15wt.% hybrid fibre weight fraction

% of sisal and cattail in the hybrid	**Thickness, h (mm)**	**Cross-sectional Area (mm^2)**	**Compressive Load (N)**	**Compressive Strength (MPa)**	**Compressive Modulus (GPa)**
0/100	7.75	193.75	3028.31	15.63(0.32)	1.56(0.107)
25/75	5.74	143.50	2525.60	17.60(0.31)	1.85(0.144)
50/50	7.07	176.75	3720.59	21.05(0.48)	2.26(0.155)
75/25	7.72	193.00	4907.99	25.43(0.11)	2.70(0.204)
100/0	8.08	202.00	4755.08	23.54(0.64)	2.33(0.135)

[a] Values in parentheses are standard deviations

4.2.4 Impact Strength of Sisal/Cattail Polyester Hybrid Composites

Table 4.10 summarizes the impact strength of the hybrid composites with a constant 50/50 (sisal/cattail) fibre blend ratio and varying hybrid fibre weight fraction from 5 to 25wt.%.

Table 4.10: Impact strength of sisal/cattail hybrid polyester composite at 50/50 sisal/cattail in the hybrid

Hybrid Fibre Weight Fraction (wt.%)	**Thickness, h (mm)**	**Cross-sectional Area (mm^2)**	**Absorbed energy (J)**	**Impact strength (kJ/m^2)**
5	3.15	31.50	0.459	14.60(3.23)
10	5.85	58.50	0.859	14.70(6.36)
15	7.07	70.70	1.639	23.19(0.69)
20	8.16	81.60	2.089	25.61(0.81)
25	9.74	97.40	1.980	20.33(0.41)

[a] Values in parentheses are standard deviations

Table 4.11 summarizes the impact strength of sisal/cattail hybrid composites with a constant fibre weight fraction of 15wt.% and varying sisal to cattail blend ratio from 0% to 100%.

Table 4.11: Impact strength of sisal/cattail hybrid polyester composite at 15wt.% hybrid fibre weight fraction

% of sisal and cattail in the hybrid	**Thickness, h (mm)**	**Cross-sectional Area (mm^2)**	**Absorbed energy (J)**	**Impact strength (kJ/m^2)**
0/100	7.75	77.50	1.68	21.68(0.51)
25/75	5.74	57.40	1.30	22.65(0.39)
50/50	7.07	70.70	1.64	23.19(0.69)
75/25	7.72	77.20	2.18	28.24(0.97)
100/0	8.08	80.80	2.78	34.40(1.44)

[a] Values in parentheses are standard deviations

4.2.5 Flexural, Tensile, Compression, Impact and Thermal Properties of Alkali Treated Hybrid Composite

Table 4.12 summarizes the flexural, tensile, compressive and impact properties of alkali treated sisal/cattail hybrid composites at a constant fibre blend ratio of 50/50 (sisal/cattail) and a constant hybrid fibre weight fraction of 15wt.%.

Table 4.12: Flexural, tensile, compression and impact properties of alkali treated hybrid composites at 50/50 sisal/cattail in the hybrid and 15wt.%

Flexural Strength (MPa)	**Flexural Modulus (GPa)**	**Tensile Strength (MPa)**	**Tensile Modulus (GPa)**	**Compressive Strength (MPa)**	**Compressive Modulus (GPa)**	**Impact Strength (kJ/m^2)**
45.68(3.68)	4.23(0.203)	33.82(0.44)	3.92(0.088)	24.98(0.38)	2.65(0.118)	27.08(0.33)

[a] Values in parentheses are standard deviations

Table 4.13 summarizes the thermal conductivity of alkali treated sisal/cattail hybrid composites with a constant fibre blend ratio of 50/50 (sisal/cattail) and a constant hybrid fibre weight fraction of 15wt.%.

Table 4.13: Thermal conductivity of alkali treated hybrid composites at 15wt.% and 50/50 sisal/cattail percentages in the hybrid

Hybrid fibre weight fractions (wt.%)	**% of sisal and cattail in the hybrid**	**Thermal Conductivity, λ (W/mK)**
15	50/50	0.7186(0.059)

[a] Values in parentheses are standard deviations

4.3 Effect of Hybrid Fibre Weight Fraction (wt.%) and Proportion of Sisal/Cattail fibres in the Hybrid (%) on the Mechanical Properties of the Hybrid Composite

4.3.1 Effect of Hybrid Fibre Weight Fraction on Mechanical Properties of the Composite at a Constant Percentage of sisal/cattail (50/50) Fibres in the Hybrid

Table 4.14 summarises the results of flexural, tensile, compressive and impact properties for sisal/cattail hybrid polyester composites at various hybrid fibre weight fractions (wt.%) and a constant percentage of sisal/cattail in the hybrid.

Table 4.14: Flexural, tensile, compressive and impact properties of sisal/cattail hybrid polyester composite at 50/50 sisal/cattail fibres in the hybrid

Hybrid Fibre weight Fraction (wt.%)	Flexural Strength (MPa)	Flexural Modulus (GPa)	Tensile Strength (MPa)	Tensile Modulus (GPa)	Compressive Strength (MPa)	Compressive Modulus (GPa)	Impact Strength (kJ/m^2)
5	27.68(1.2)	2.09(0.199)	16.64(1.86)	1.37(0.065)	16.52(0.43)	0.99(0.109)	14.60(3.23)
10	31.56(2.6)	3.04(0.182)	24.22(2.44)	2.62(0.209)	18.78(0.25)	1.48(0.112)	14.70(6.36)
15	36.65(2.6)	3.83(0.137)	28.29(1.25)	3.47(0.233)	21.05(0.48)	2.26(0.155)	23.19(0.69)
20	44.92 (4.4)	4.45(0.326)	31.40(0.23)	3.81(0.217)	23.99(0.16)	2.82(0.138)	25.61(0.81)
25	37.99 (2.5)	3.85(0.100)	26.31(0.22)	2.50(0.124)	19.60(0.29)	2.46(0.236)	20.33(0.41)

[a] Values in parentheses are standard deviations

4.3.1.1 Flexural, Tensile and Compressive Strengths

The results of the effect of hybrid fibre weight fraction at 50/50 (constant) percentage of cattail/sisal in the composites on flexural, tensile and compressive strengths are as shown in Figure 4.3 and were developed from the data in Table 4.14.

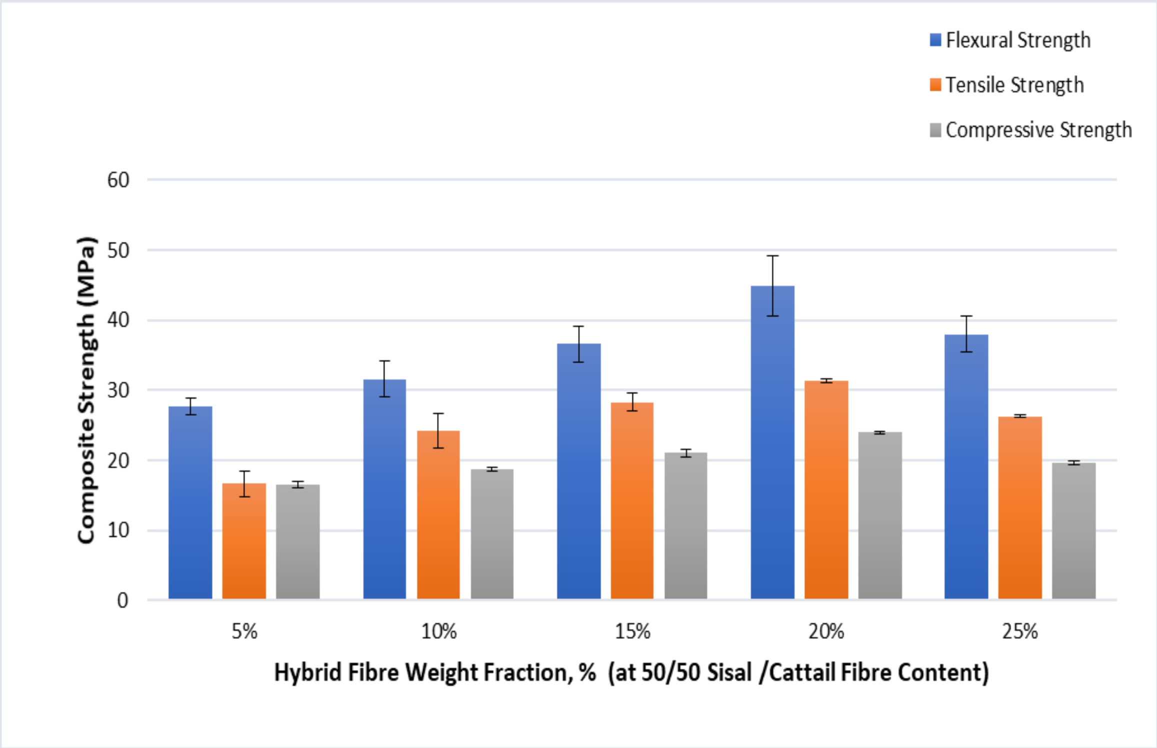


Figure 4.3: Effect of hybrid fibre weight fraction at 50/50 sisal/cattail fibre content on flexural, tensile and compressive strengths of the composites.

At a constant percentage of cattail/sisal in the hybrid composite, an increasing trend was seen in flexural, tensile and compressive strengths as the hybrid fibre weight fraction (wt.%) increased up to 20wt.% followed by a drop at 25wt.%. For instance, from 5-

20wt.%, there was an increase by 62.28%, 88.7% and 45.22% in flexural, tensile and compressive strengths respectively. Table 4.15 shows the analysis of variance for flexural, tensile and compressive strength. The *p*-values for flexural, tensile and compressive strengths were noted to be less than 0.05, implying significant differences between the means of various composites formed by varying hybrid fibre loadings (wt.%). Likewise, ANOVA showed higher calculated F-values as compared to F-critical values, further suggesting a significant difference in their performance.

Table 4.15: Analysis of Variance for flexural, tensile and compressive strengths of composites with varying hybrid fibre weight fraction (wt.%) and 50/50 sisal/cattail fibres in the hybrid

ANOVA ANALYSIS							
Properties	**Source of Variation**	**SS**	**df**	**MS**	**F**	***p*-value**	**F-critical**
Flexural Strength	Between Groups	864.35	4	216.09	***21.45***	5.3E-07	***2.87***
	Within Groups	201.45	20	10.07			
	Total	1065.79	24				
Tensile Strength	Between Groups	617.17	4	154.29	***55.65***	1.47E-10	***2.87***
	Within Groups	55.45	20	2.77			
	Total	672.61	24				
Compressive Strength	Between Groups	154.14	4	38.53	***257.32***	6.84E-17	***2.87***
	Within Groups	2.99	20	0.15			
	Total	157.13	24				

This phenomenon is consistent with previous studies (Bichang'a & Ayub, 2017; Ondiek et al., 2018) and may be attributed to the increase in the amount of fibres as load bearing elements in the composite and their uniform distribution in the matrix, as fibre loading increased to 20wt.% (Figure 4.4) resulting to better fibre-matrix interfacial adhesion. This therefore ensures that the resultant stress due to an applied load is disseminated uniformly within the composite material (Vimalanathan et al., 2016). Maximum tensile strengths of 31.40 MPa were attained at 20wt.% hybrid fibre weight fraction at a constant percentage of cattail/sisal fibres in the composite. The tensile strength results obtained in this research work are comparable with other studies done on natural fibres reinforced polymer composites reported in literature. For instance, Joseph et. al., (1999) reported a tensile strength of 31.12 MPa for a sisal-reinforced polyethylene composite at 30wt.%. Further, Wambua et al., (2003) reported a tensile strength of sisal reinforced polypropylene composite (40wt.%) to be approximately 30 MPa. Similarly, a maximum flexural strength of 44.92 MPa was reported at 20wt.% and a constant percentage of cattail/sisal fibres in the composite. This was close to previous study findings reported on hybrid epoxy composites reinforced with short fibres and micro ceramic particles where the authors reported a flexural strength of 36.84 MPa for a sisal fibre length of 4 mm and 10wt.% cement particles (Santos, Batista, Panzera, Christoforo, & Rubio, 2017). In addition, a research investigating the effect of fibre length and weight percentage on mechanical properties of composites recorded a tensile strength of 38.80 MPa for 15 mm fibre length at 12wt.% (Venkateshwaran et al., 2011). A similar pattern of increasing flexural and tensile strength with increase in hybrid fibre loading to a certain level was reported previously (Akash et al., 2016; Gupta et al., 2016; Vimalanathan et al., 2016). On the other hand, a maximum compressive strength of 23.99 MPa was reported at 20wt.% hybrid fibre weight fraction (Reddy & Hussain, 2013). This trend may be attributed to better fibre-matrix bond due to uniform distribution of fibres and the presence of more sisal fibres in the composite (Sivasubramanian et al., 2013).

Flexural, tensile and compression strengths decreased by 15.43%, 16.21% and 18.29% respectively as the hybrid fibre weight fraction was increased from 20 to 25wt.%. This maybe because of poor interfacial bonding between the fibres and the matrix as a result of reduced fibre wetting by the matrix at fibre loadings of more than 20 wt.% that leads to uneven distribution of the load (Vimalanathan et al., 2016).

Figure 4.4: Micrograph of hybrid composite with 15wt.% and constant percentage of sisal/cattail fibres in the composite.

Figure 4.5 shows a fracture micrograph of tensile investigation test for the hybrid composite at 20wt.% hybrid fibre weight fraction and a constant (50/50) percentage of sisal/cattail fibre in the hybrid. From these images, a relatively higher percentage of fibre fracture was observed with more of these breakages being cattail fibres. Likewise, there were substantial fibre pull-outs noted, most of them being sisal fibres. Higher percentage of fibre breakages (cattail>sisal) may be attributed to increase of fibre to resin ratio from 5-20wt.%. Further, serrated breakages of cattail fibres at the fractured edge of the composites instead of fibre-pull-outs were observed, possibly because these fibres exhibit low tensile strengths (due to its low cellulose content) as compared to sisal fibres (Table 4.3). On the other hand, serrated and twisted ends of sisal fibres observed, may be attributed to good interfacial bonding and better strength of the fibres. Therefore, the failure mechanism noted here was fibre pull-out (mainly sisal fibres) and fibre fracture (high in cattail fibres and followed by some in sisal fibres).

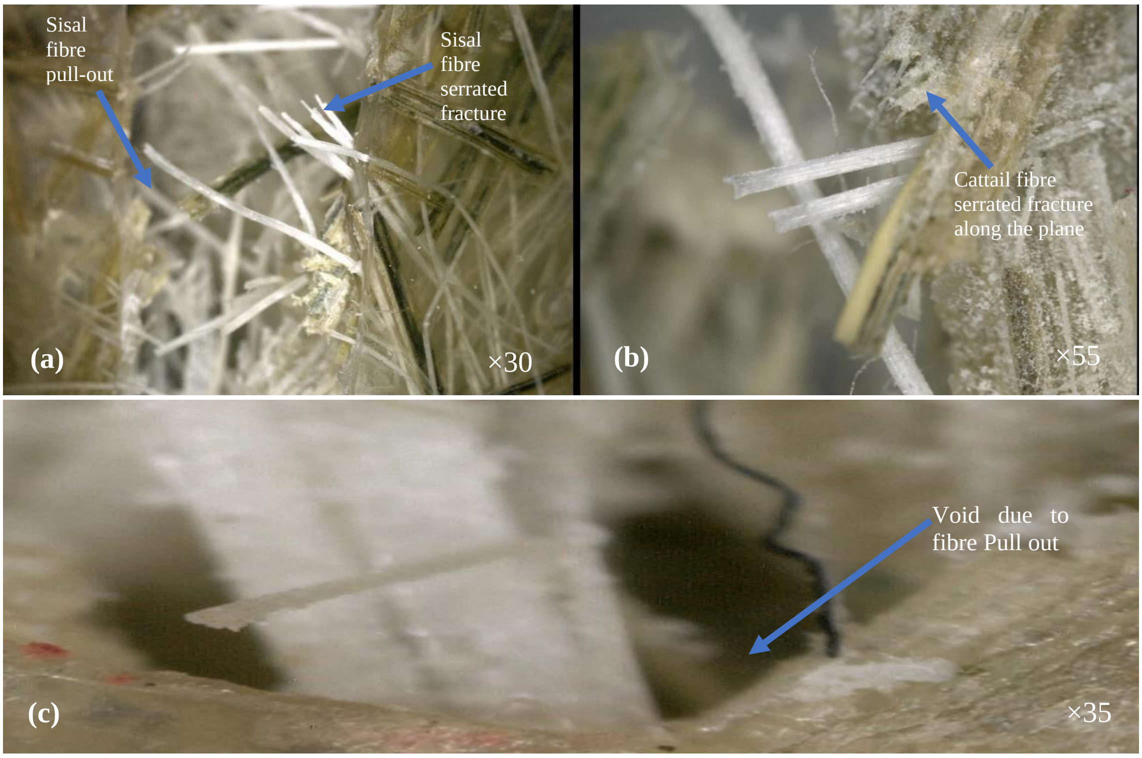


Figure 4.5: Hybrid composite at 20wt.% hybrid fibre weight fraction and 50/50 sisal/cattail fibre content in the hybrid after tensile test

4.3.1.2 Flexural, Tensile and Compressive Moduli

Effect of hybrid fibre weight fraction (wt.%) at a constant percentage of sisal/cattail fibres in the hybrid on flexural, tensile and compressive modulus is illustrated in Figure 4.6.

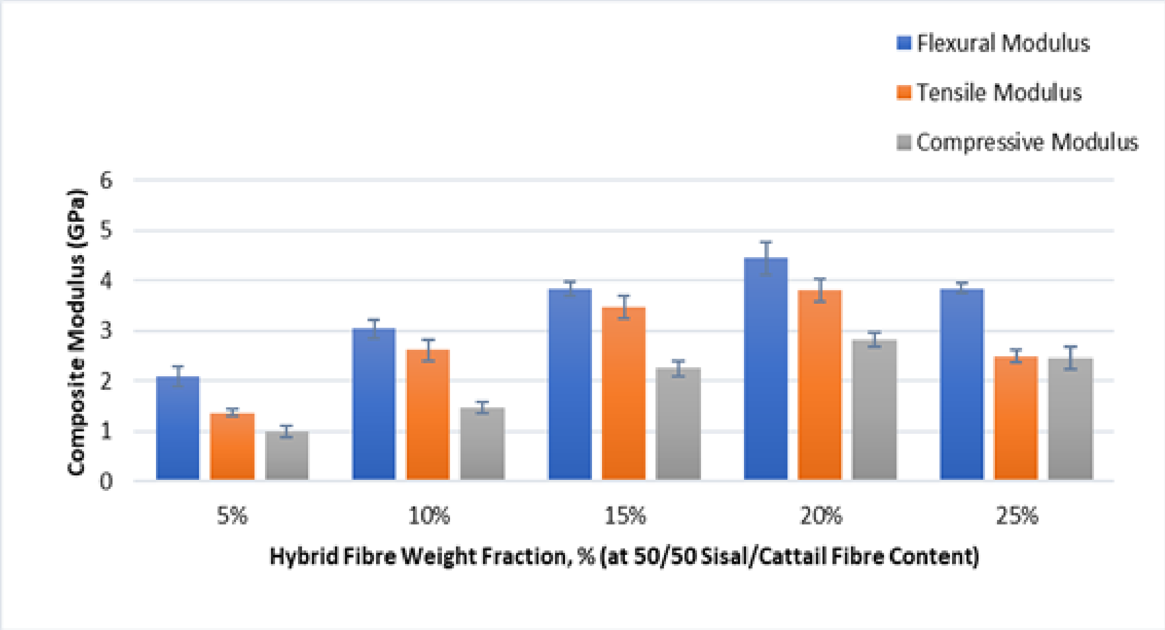


Figure 4.6: Effect of hybrid fibre weight fraction at a constant (50/50) sisal/cattail fibre content on flexural, tensile and compressive moduli of the composites

The flexural moduli of the hybrid composites increased by 45.32%, 25.99% and 16.19% as the fibre loading increased from 5-10 wt.%, 10-15 wt.% and 15-20 wt.% respectively with a maximum value of 4.45 GPa. However, this is not the case between 20-25wt.% fibre loading as the flexural modulus decreased by 13.48%. ANOVA for flexural, tensile and compressive modulus of hybrid composites is shown in Table 4.16. From the analysis, it can be seen that the calculated F-values are higher than F-critical values suggesting that the hybrid composites fabricated by varying hybrid weight fractions perform differently. This is also supported by the fact that *p*-values are less than 0.05.

Table 4.16: Analysis of Variance for flexural, tensile and compressive modulus of the composite with varying hybrid fibre weight fraction and 50/50 sisal/cattail fibres content

ANOVA ANALYSIS

Properties	**Source of Variation**	**SS**	**df**	**MS**	**F**	**P-value**	**F critical**
Flexural modulus	Between Groups	16.55132	4	4.13783	***79.78232***	5.3E-12	***2.866081***
	Within Groups	1.03728	20	0.051864			
	Total	17.5886	24				
Tensile Modulus	Between Groups	18.03386	4	4.508464	***109.7324***	2.61E-13	***2.866081***
	Within Groups	0.82172	20	0.041086			
	Total	18.85558	24				
Compressive Modulus	Between Groups	11.09834	4	2.774586	***59.28603***	8.28E-11	***2.866081***
	Within Groups	0.936	20	0.0468			
	Total	12.03434	24				

The increase in flexural moduli between 5-20 wt.% may be because polyester resin transmits and uniformly distributes the applied stress to sisal/cattail fibres in the composite. This is attributed to the increase in the amount of load bearing elements, fibres, and their uniform distribution within the composites thus making the composites stiffer. The drop of flexural properties at higher hybrid fibre weight fraction (20-25wt.%) could be due to poor impregnation of fibres by the resin and creation of air spaces during fabrication process leading to the formation of voids within the composites. The results obtained in this study are comparable with those of (Sana et al., 2015) on flexural properties of cattail fibre reinforced composites with polyester resin in which a flexural moduli of 4.80GPa for sea water and NaOH treated fibres at 10.3% fibre loading was registered. However, there were some degree of disparities with other researchers. For instance, cattail /polypropylene (PP) fibre at 70 wt.% showed a flexural modulus of 5.99 GPa (Liu et al., 2013) and *Shorea robusta*/polyester composite showed a flexural modulus of 1.81 GPa at 20% hybrid fibre loading. This can be attributed to composite fabrication techniques used, form of the fibres used (long/short), fibre extraction method used and the mechanical properties of the resin used among other possible reasons. On the other hand, tensile moduli of the resultant composites improved as the hybrid fibre loading increased from 5-10wt.%, 10-15wt.% and 15-20wt.% by 91.24%, 32.44% and 9.79% respectively to attain a maximum tensile modulus of 3.81GPa. Further, compressive moduli of the composites increased by 49.49%, 52.70% and 24.78% as the hybrid fibre loading increased from 5-10wt.%, 10-15wt.% and 15-20wt.%. The trend noted here on the increase in tensile and compressive moduli with increase in cattail/sisal fibre loading in the resultant composite can be attributed to addition of more fibres in the matrix, uniform distribution of these fibres in the matrix and proper impregnation of fibre by the matrix. The increasing pattern in tensile and compressive moduli is comparable with previous findings. Bichang'a and Ayub (2017) investigating the effect of fibre loading on mechanical properties of woven sisal fabric reinforced epoxy composites reported an increase of tensile modulus with increase in fibre weight fraction from 30-50 wt.% to 50-60wt.%. Further, a close tensile moduli of 3.09GPa was reported by Joseph et al. (1999) investigating the effect of processing variables on the mechanical properties of sisal fibre reinforced polypropylene composites. Similar trends were also reported by Vimalanathan et al. (2016) and Ondiek et al. (2018) studying the mechanical, dynamic mechanical and thermal analysis of *Shorea robusta* dispersed composites and investigating the effect of fibre concentration and fibre size on mechanical properties of rice husk fibre reinforced polyester composites respectively. Further addition of fibres i.e. 20-25wt.% lead to a drop in tensile and compressive modulus. This can be attributed to un-uniform distribution of stresses due to the development of large stresses at low strains (Gupta et al., 2016).

4.3.1.3 Impact strength

The results on varying hybrid fibre weight fraction at a constant percentage of sisal/cattail (50/50) fibre in the hybrid are as shown in Figure 4.7.

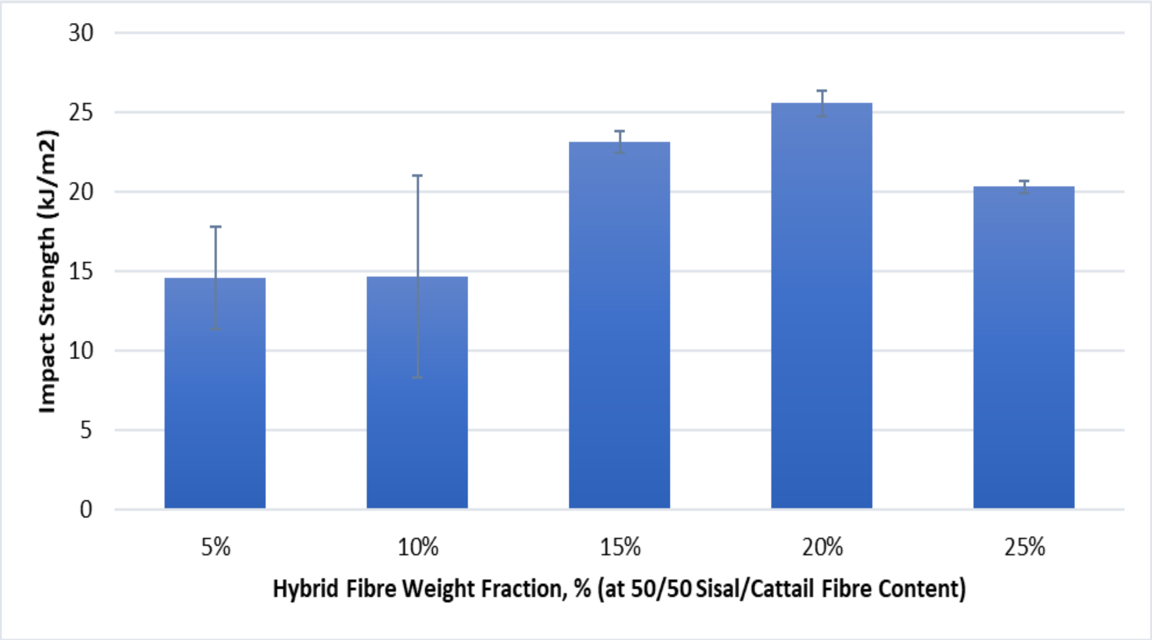


Figure 4.7: Effect of hybrid fibre weight fraction at a constant (50/50) sisal/cattail fibre content on impact strength of the composites

There was no change in impact strength as the fibre loading increased from 5-10wt.%. This may be attributed to the brittle nature of the resultant sisal/cattail hybrid composite; low fibre loadings result in less longitudinal fibres at the impacted area which results to a decrease in resistance to crack propagation. Further, there was no observed difference in failure modes of the composites within this range. Besides, loading of sisal/cattail fibres from 10-20wt.% resulted in a moderate increase of impact strength to attain an optimum impact strength of 25.61 kJ/m^2 followed by a drop of 20.62% when fibre loading increased from 20-25wt.%. These are comparable to that obtained by Vimalanathan et al. (2016) where no increase in impact strength was reported as fibre loading increased from 5-10wt.% , a moderate increase of impact strength between 10-20wt.% which again reduced at 25wt.% . Reduction of impact strength between 20-25wt.% may be due to the increase in fibre-to-fibre contact resulting to fibre agglomeration which eventually leads to a drop-in fibre-matrix stress transfer. Larger serrated fracture surfaces were observed at 20wt.% as compared to other composites which had more less sharp fractures. This may be the reason why high impact strengths were reported at 20wt.%. The serrated fractures has been previously reported to absorb more impact energy (Wambua et al., 2003).

Table 4.17: Analysis of Variance for impact strength of hybrid composites with varying hybrid fibre weight fraction (wt.%) and 50/50 sisal/cattail fibres in the hybrid

ANOVA ANALYSIS						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F critical**
Between Groups	2.09E+10	4	5.21E+09	**62.20486**	5.33E-11	**2.866081**
Within Groups	1.68E+09	20	83802918			
Total	2.25E+10	24				

Analysis of variance for impact strength was done and high calculated F-value was observed as compared to F-critical value, suggesting that all hybrid composites at different hybrid fibre weight fractions were significantly different from each other. Likewise, the reported *p*-value was less than 0.05 (Table 4.17).

4.3.2 Effect of Varying the Percentage of Sisal/Cattail Fibre Content in the Hybrid at a Constant Hybrid Fibre Weight Fraction of 15wt.%

Summarised test result reports for flexural, tensile, compressive and impact properties of sisal/cattail hybrid polyester composites at various percentages of sisal/cattail fibre in the hybrid at a constant hybrid fibre weight fraction of 15wt.% are shown in Table 4.18.

Table 4.18: Flexural, tensile, compressive and impact properties of sisal/cattail hybrid polyester composite at 15% hybrid fibre weight fraction

% of sisal/cattail in the hybrid	Flexural Strength (MPa)	Flexural Modulus (GPa)	Tensile Strength (MPa)	Tensile Modulus (GPa)	Compressive Strength (MPa)	Compressive Modulus (GPa)	Impact Strength (kJ/m^2)
0/100	20.72(1.76)	2.72(0.126)	18.46(0.98)	2.05(0.139)	15.63(0.32)	1.56(0.107)	21.68(0.51)
25/75	24.51(1.36)	3.04(0.137)	22.93(0.63)	2.57(0.166)	17.60(0.31)	1.85(0.144)	22.65(0.39)
50/50	34.98(4.80)	3.83(0.137)	28.29(1.25)	3.47(0.233)	21.05(0.48)	2.26(0.155)	23.19(0.69)
75/25	45.97(4.29)	4.26(0.225)	32.39(0.72)	3.82(0.108)	25.43(0.11)	2.70(0.204)	28.24(0.97)
100/0	31.63(4.30)	2.98(0.083)	27.67(1.43)	2.73(0.144)	23.54(0.64)	2.33(0.135)	34.40(1.44)

[a] Values in parentheses corresponds to standard deviation

4.3.2.1 Flexural, Tensile and Compressive Strengths

The findings on varying the percentages of sisal/cattail fibre content in the hybrid on flexural, tensile and compressive strengths of short randomly oriented and intimately mixed sisal/cattail fibre reinforced polyester composites at a constant hybrid fibre weight fraction of 15wt.% is illustrated in Figure 4.8.

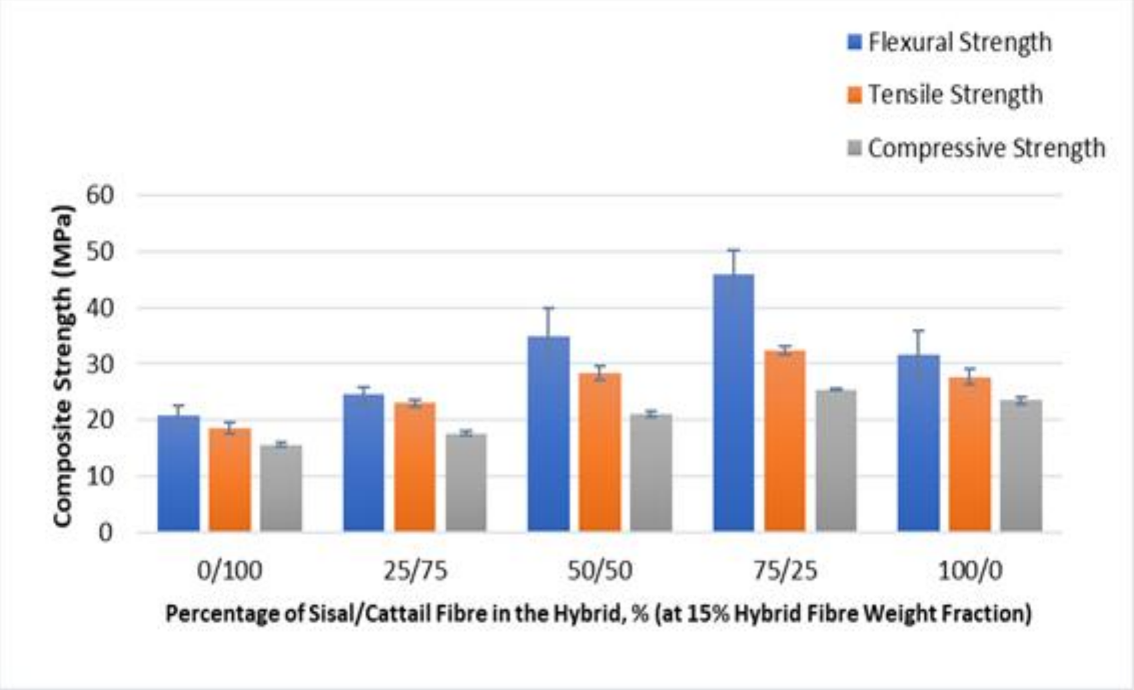


Figure 4.8: Effect of the percentage of sisal/cattail fibres in the hybrid at a constant hybrid fibre weight fraction of 15wt.% on tensile, flexural and compressive strengths of the composites

It is evident from Figure 4.8 that flexural, tensile and compressive strengths increased as the percentage of sisal fibre in the hybrid increased from 0-75% or cattail fibre decreased from 100-25% to attain maximum values at 75/25 sisal/cattail. From 0/100-75/25 sisal/cattail, there was an increase in flexural, tensile and compressive strengths by 121.86%, 75.46% and 62.69% respectively. ANOVA was done (Table 4.19) to establish the significance of this trend for flexural, tensile and compressive strengths.

Table 4.19: Analysis of Variance for flexural, tensile and compressive strengths with varying percentages of sisal/cattail fibres in the hybrid at 15wt.% fibre weight fraction

ANOVA ANALYSIS							
Properties	**Source of Variation**	**SS**	**df**	**MS**	**F**	***p*-value**	**F critical**
Flexural Strength	Between Groups	1996.09	4	499.0245	***17.2605***	2.86E-06	***2.866081***
	Within Groups	578.23	20	28.91136			
	Total	2574.33	24				
Tensile Strength	Between Groups	592.54	4	148.1339	***140.8631***	2.3872E-14	***2.866081***
	Within Groups	21.03	20	1.051616			
	Total	613.57	24				
Compressive Strength	Between Groups	338.31	4	84.57711	***211.8071***	4.58E-16	***2.866081***
	Within Groups	7.99	20	0.399312			
	Total	346.29	24				

From Table 4.19, it can be concluded that flexural, tensile and compressive modulus of composites fabricated with different percentages of sisal/cattail fibres in the hybrid at a constant hybrid fibre weight fraction of 15wt.% are significantly different from each other. This is evident as the calculated F-values are higher than F-critical values as well as a *p*-values are less than 0.05.

Furthermore, as the percentage of sisal fibre loading increased in the hybrid from 75% to 100%, a drop by 31.19%, 14.57% and 7.43% in flexural, tensile and compressive strengths was observed. This behaviour can be attributed to fibre agglomeration caused by higher sisal fibre loading which leads to decrease in stress transfer between sisal/cattail fibres and the matrix. A similar trend of increase in flexural, tensile and compressive strengths of the hybrid composites to a certain level has been reported in literature by Idicula et al. (2010). It is worth noting from the results obtained (Figure 4.8) that flexural, tensile and compressive strengths of the hybrid composites are higher than unhybridized cattail fibre reinforced polyester composites. This is a clear indication of a positive hybridisation effect on cattail fibres (Bajwa et al., 2015). This can be attributed to better dispersion of fibres in the hybrid compared to those fabricated from 100% cattail fibres (Idicula et al., 2010). At all percentages of sisal/cattail fibre content in the hybrid at

15wt.%, flexural, tensile and compressive strengths were maximum at 75/25 sisal/cattail fibre content with values of 45.97MPa, 32.39MPa and 25.43MPa respectively. At 15wt.% hybrid fibre weight fraction, flexural, tensile and compressive strengths of cattail/polyester composites were much lower compared to sisal/polyester composite and hybrid composites. This trend can be explained from the fact that, the tensile properties of sisal fibre are higher than cattail fibre (Table 4.3) implying that the reinforcing effect of sisal fibre in the matrix is better than that of cattail fibres. In addition, the diameter of sisal fibre is less than the diameter of cattail fibre and therefore the surface area of the fibre exposed to the matrix is higher in sisal/polyester composites than that of cattail/polyester composites. This therefore ensures good physical interaction between the fibres and the matrix as well as better stress transfer between the fibres and the matrix in sisal fibre reinforced composites. This explains the reason behind the trend noted in this study where flexural, tensile and compressive strengths increase with increase of sisal fibres in the hybrid from 0%-75% as synergism is created (Idicula et al., 2010). Teja et al., (2016) studying mechanical and thermal properties of polyester composites reinforced with sisal and SiC powder reported a close tensile strength value of 28.60 MPa at 30wt.% sisal/polyester composites. Santhosh et al., (2014) fabricated composites with banana and coconut shell powder in epoxy and vinyl ester resin and reported tensile strengths of 19.76MPa and 19.61MPa respectively.

At 15wt.% hybrid fibre fraction and 75/25 sisal/cattail fibre content, higher fibre pull-out and low fibre fracture were observed (Figure 4.9). This is because there were only 25% cattail fibres as compared to sisal fibres (75%). Thus, the low strength of cattail fibres due to their low cellulose content (Table 4.3) resulted in most breakages. Since the strength of sisal fibres was better, sisal fibre pull-outs and breakages were noted. Thus, the composites had better mechanical properties.

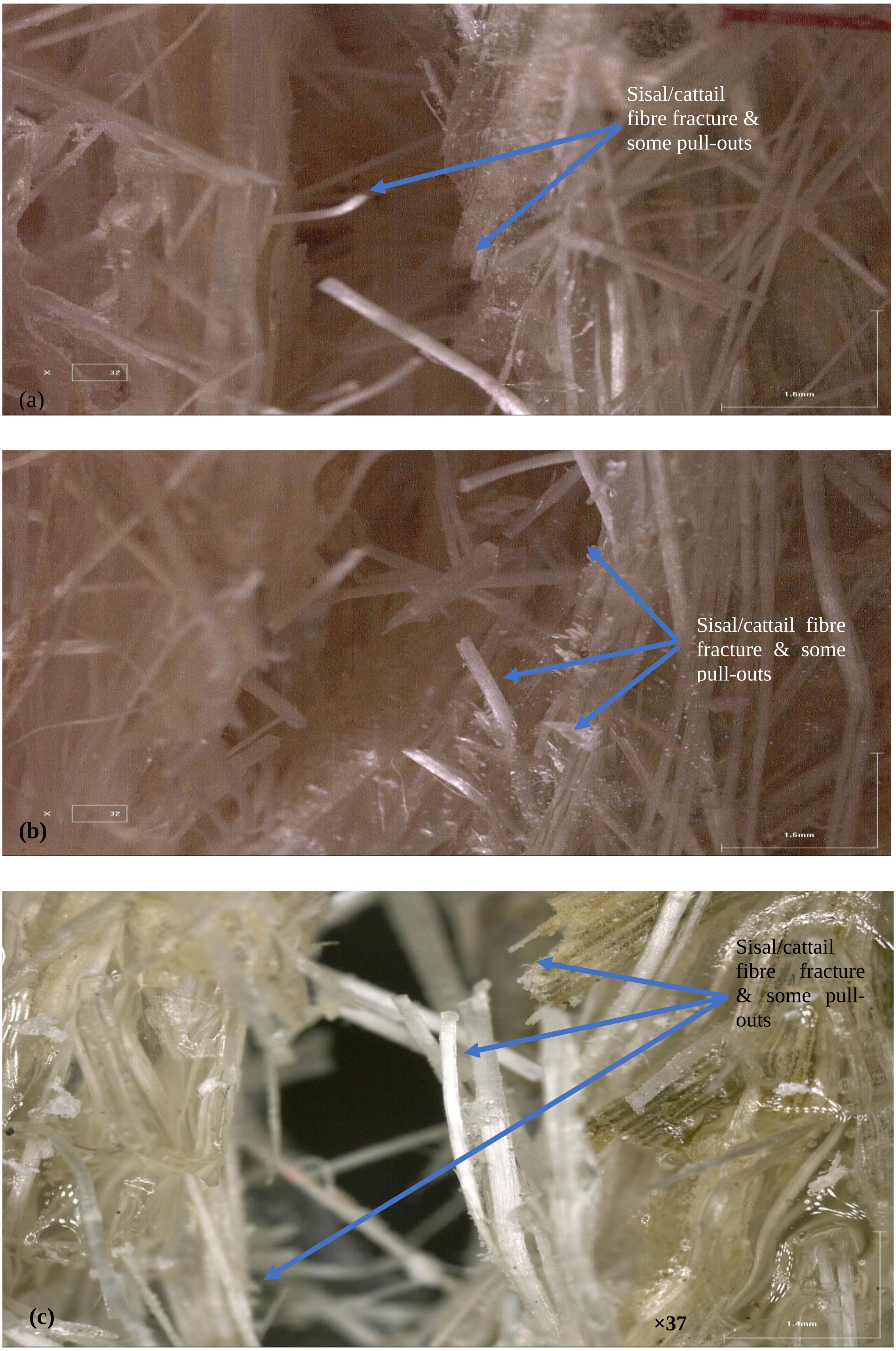


Figure 4.9: Hybrid composite at 15wt.% hybrid fibre weight fraction and 75/25 sisal/cattail fibre content in the hybrid after tensile test

4.3.2.2 Flexural, Tensile and Compressive Moduli

Figure 4.10 below illustrates flexural, tensile and compressive moduli of a randomly oriented hybrid composite at a constant hybrid fibre weight fraction of 15wt.% and different percentages of sisal/cattail fibre content in the hybrid composite.

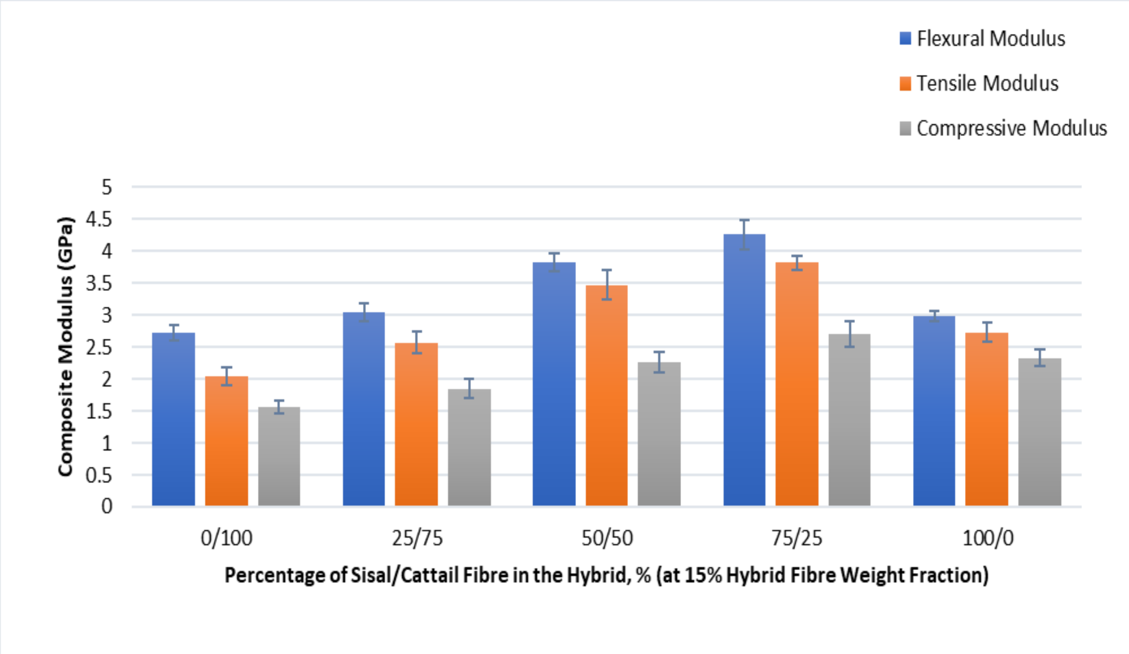


Figure 4.10: Effect of the percentage of sisal/cattail fibres in the hybrid at a constant hybrid fibre weight fraction of 15wt.% on tensile, flexural and compressive moduli of the composites

The flexural, tensile and compressive moduli of the hybrid composites increased as the proportion of sisal fibres in the hybrid increased from 0%-75% to give peak values of 4.26 GPa, 3.82 GPa and 2.70 GPa respectively. Further increase in the percentage of sisal in the hybrid from 75%-100% resulted in a decrease in flexural, tensile and compressive moduli by 30.05%, 28.53% and 13.7% respectively. From Table 4.20, the calculated F-values for flexural, tensile and compressive modulus were higher compared to F-critical values, suggesting there was a significant difference between various composites fabricated by different percentages of sisal/cattail fibres in the hybrid. Furthermore, the small *p*-value (less than 0.05) indicates that composites fabricated from various sisal/cattail blends perform differently.

Table 4.20: Analysis of variance for flexural, tensile and compressive modulus with varying percentages of sisal/cattail fibres in the hybrid at 15wt.% fibre weight fraction

ANOVA ANALYSIS							
Properties	**Source of Variation**	**SS**	**df**	**MS**	**F**	**P-value**	**F critical**
Flexural Modulus	Between Groups	7.94336	4	1.98584	***44.76***	1.05E-09	***2.866081***
	Within Groups	0.88724	20	0.044362			
	Total	8.8306	24				
Tensile Modulus	Between Groups	10.06776	4	2.51694	***75.49***	8.88E-12	***2.866081***
	Within Groups	0.66684	20	0.033342			
	Total	10.7346	24				
Compressive Modulus	Between Groups	3.964184	4	0.991046	***22.04***	4.27E-07	***2.866081***
	Within Groups	0.89908	20	0.044954			
	Total	4.863264	24				

This increasing trend of flexural, tensile and compressive moduli of the composite with increase of the percentage of sisal fibres in the hybrid from 0%-75% can be attributed to higher compatibility and uniform distribution of fibres in the matrix resulting in good transfer of stress between the matrix and the fibres as explained before. The decrease in flexural, tensile and compressive moduli of composites at higher sisal fibre loading results to fibre agglomeration and therefore poor fibre-matrix bond. A positive hybrid effect was also seen in the flexural, tensile and compressive moduli as was the case in flexural, tensile and compressive strengths where cattail/polyester composite modulus is much lower compared to sisal/polyester composite and the other hybrid composites. A similar pattern was reported by Idicula et al. (2010) while investigating the effect of varying the fibre ratio of banana and sisal fibre on flexural and tensile modulus of the composite at different fibre loadings. Likewise, Bajwa et al. (2015) evaluating some mechanical properties of cattail composites reported a similar relationship where 75/25 cattail/wheat straw/ PMDI composite panel had the highest tensile modulus of 17.95 MPa.

4.3.2.3 Impact Strength

Figure 4.11 delineates the effect of varying the percentage of sisal/cattail fibre content in the hybrid at a constant hybrid fibre weight fraction of 15wt.% on impact strength.

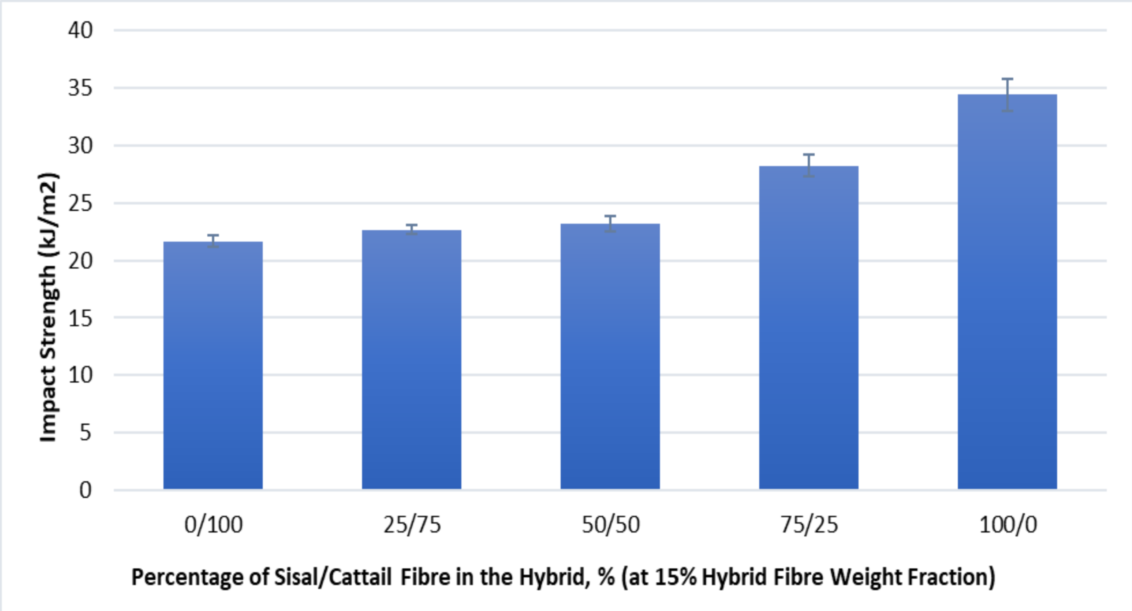


Figure 4.11: Effect of percentage of sisal/cattail fibres in the hybrid at a constant hybrid weight fraction of 15 wt.% on impact strength of the composites

It can be clearly observed that impact strength of hybrid composites improved steadily by 58.67% as the percentage of sisal fibre increased from 0% to 100% to attain a peak value of 34.40 kJ/m^2 at 100/0 sisal/cattail composition. Table 4.21 shows ANOVA conducted on impact strength results to confirm their significance.

Table 4.21: Analysis of Variance for impact strength with varying percentages of sisal/cattail fibres in the hybrid at 15wt.% hybrid fibre weight fraction

ANOVA ANALYSIS						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F critical**
Between Groups	457.1191	4	114.2798	**86.40094**	2.51E-12	**2.866081**
Within Groups	26.45336	20	1.322668			
Total	483.5724	24				

As seen in Table 4.21, the calculated F-value is higher than the F-critical value, suggesting a significant difference between means of various blends in the hybrid forming the composite. This analysis therefore implies a significant difference in impact strengths at various sisal/cattail fibre combinations in the resultant composite. Steady increase of impact strength with increase of sisal fibre loading, could be because of the porous nature of sisal fibres and their high microfibrillar angle (Bledzki & Gassan, 1999). Therefore, impact strength increased as sisal fibre in the hybrid increased. Hence, it can be seen that there is a negative hybrid effect in impact strength since sisal/polyester composite revealed better impact strength than cattail/polyester and other hybrid composites. This trend has been reported in previous studies (Idicula et al., 2010). Further, Sivasubramanian et al. (2013) studying the mechanical properties of hybrid polyester composites reinforced with sisal/banana fibres reported better impact strengths for sisal/polyester composites followed by sisal/banana polyester and lastly banana/polyester composites. On the other hand, Ramesh et al., (2013) evaluating the mechanical properties of a hybrid polyester composite reinforced with sisal/jute/GFRPs reported a higher impact strength for sisal/GFRP/Polyester composite as compared to jute/GFRP/polyester composites. Venkateshwaran et al. (2011) reported a comparable trend with an impact strength of 22.54 kJ/m^2 for 0/100 banana/sisal blend.

4.3.3 Effect of Alkali Treatment on the Mechanical and Thermal Properties of Hybrid Composites (15wt.% Hybrid Weight Fraction and 50/50 Sisal/Cattail Fibre Percentage)

Table 4.22 summarizes the results of flexural, tensile, compressive and impact strengths of alkali treated and untreated sisal/cattail hybrid polyester composites at a constant percentage of sisal/cattail fibres in the hybrid and hybrid fibre weight fraction of 50/50 and 15wt.% respectively.

Table 4.22: Flexural, tensile, compressive and impact properties of alkali treated and untreated sisal/cattail hybrid polyester composite at 50/50 sisal/cattail in the hybrid and 15wt.%

	Flexural Strength (MPa)	Flexural Modulus (GPa)	Tensile Strength (MPa)	Tensile Modulus (GPa)	Compressive Strength (MPa)	Compressive Modulus (GPa)	Impact Strength (kJ/m^2)
Alkali Treated	45.68(3.68)	4.23(0.203)	33.82(0.44)	3.92(0.088)	24.98(0.38)	2.65(0.118)	27.08(0.33)
Untreated	36.65(2.60)	3.83(0.137)	28.29(1.25)	3.47(0.233)	21.05(0.48)	2.26(0.155)	23.19(0.69)

[a] Values in parentheses are standard deviations.

4.3.3.1 Effect of Alkali treatment on flexural, tensile and compressive strengths of the composites at 15wt.% hybrid weight fraction and 50/50 sisal/cattail fibre content in the hybrid.

The chart below illustrates the effect of alkali treatment on flexural, tensile and compressive strengths of the composite at 15wt.% hybrid fibre weight fraction and 50/50 sisal/cattail fibre percentages in the hybrid as developed from data in Table 4.22.

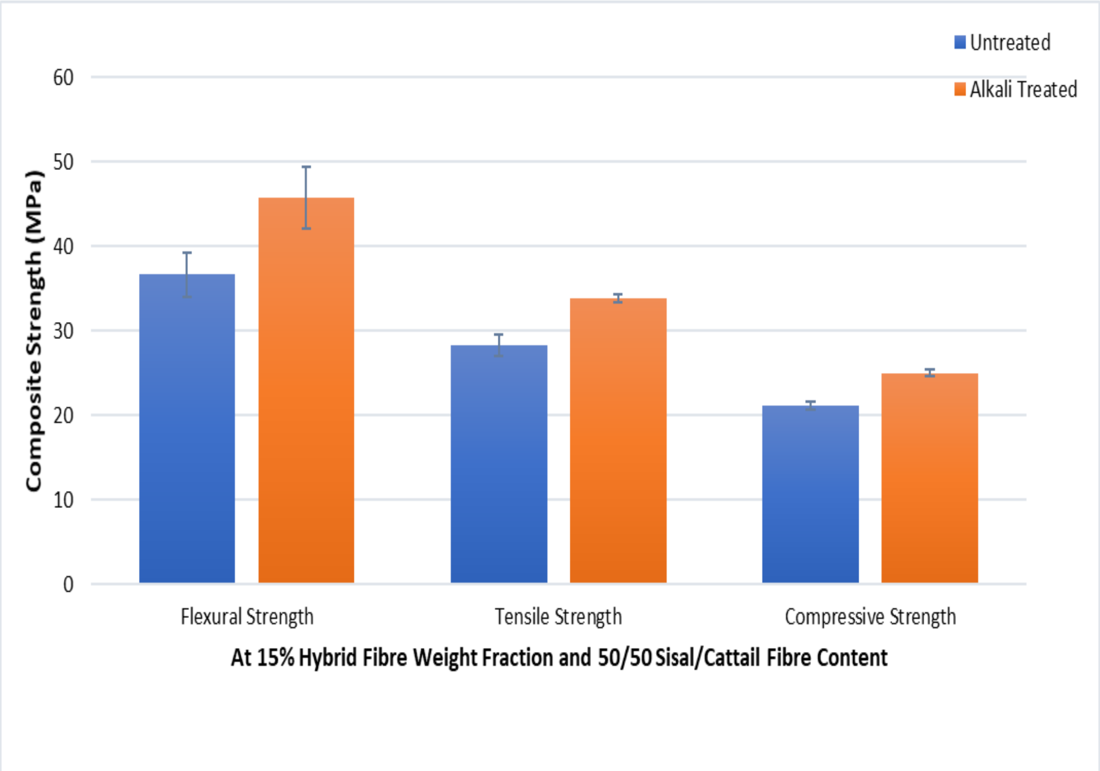


Figure 4.12: Effect of alkali treatment on flexural, tensile and compressive strengths of the hybrid composites at 15wt.% and 50/50 sisal/cattail content in the hybrid.

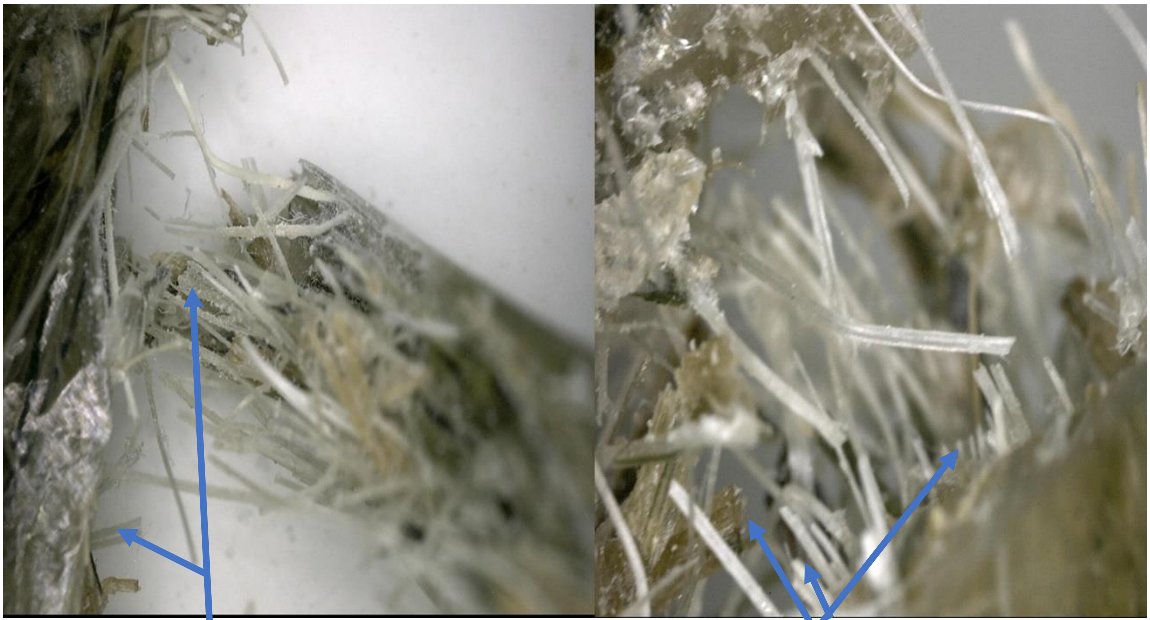
Composites prepared from treated sisal and cattail fibre reinforcements (Figure 4.12), exhibited better mechanical properties than similar composites made from untreated fibres. Flexural, tensile and compressive strengths improved by 24.64%, 19.55% and 18.67% respectively with alkali treatment. From Table 4.23, the calculated absolute T-values are higher in flexural, tensile and compressive strengths than the two tailed t-critical values, thus suggesting that there is a significant difference between the mean values for treated and untreated hybrid composites.

Table 4.23: Paired T-test analysis for flexural, tensile and compressive strengths of sisal/cattail polyester composite at 15wt.% and 50/50 sisal/cattail content

T-test Analysis-Flexural Strength			**T-test Analysis-Tensile Strength**			**T-test Analysis-Compressive Strength**		
	Untreated	Treated		Untreated	Treated		Untreated	Treated
Mean	36.64	45.68	Mean	28.29	33.82	Mean	21.05	24.98
Variance	8.49	31.60	Variance	1.94	0.25	Variance	0.29	0.18
Observations	5	5	Observations	5	5	Observations	5	5
Pearson Corr.	0.956		Pearson Corr.	0.51		Pearson Corr.	0.04	
H. Mean Dif.	0		H. Mean Dif.	0		H. Mean Dif.	0	
df	4		df	4		df	4	
t Stat	***-3.90***		t Stat	***-10.16***		t Stat	***-13.0***	
P(T<=t) one-tail	0.0088		P(T<=t) one-tail	0.0003		P(T<=t) one-tail	0.0001	
t Critical one-tail	2.13		t Critical one-tail	2.13		t Critical one-tail	2.13	
P(T<=t) two-tail	***0.018***		P(T<=t) two-tail	***0.0005***		P(T<=t) two-tail	***0.0002***	
t Critical two-tail	***2.78***		t Critical two-tail	***2.78***		t Critical two-tail	***2.78***	

The T-test analysis therefore indicated that there was a significant difference between mechanical properties of treated and untreated sisal/cattail fibre reinforced polyester composites. Figures 4.13a-d show high-resolution fracture behaviour micrograph after tensile testing of treated and untreated hybrid composites both at 15wt.% hybrid fibre weight fraction and 50/50 percentages of sisal/cattail fibre content in the hybrid. Fibre pull-out from the matrix was observed in untreated fibre hybrid composites signifying poor adhesion and interaction between the fibres and the matrix. Minimal cattail fibre-pull outs were observed and this could be due to their lower strength and thus resulting to their breakages as compared to sisal fibres.

(a) Fibre pull-out (×30) (b) Fibre pull-out (×25)



(c) Fibre-fracture along a plane (×17) (d) High fibre-fracture and minimal pull-out (×35)

Figure 4.13: Micrographs after tensile tests of composites with (a-b) Untreated (c-d) Treated fibres

However, with treated hybrid composites (Figures 4.13c-d), there were fewer fibre pull-outs but more fibre fracture and twisting at the broken ends indicating a relatively strong bond between the fibres and the matrix. Higher breakages of cattail fibres were also observed in treated hybrid composites, and this could be due to their low strength as compared to sisal fibres. Lower strength of cattail fibres in this work compared to figures from literature may be attributed to the extraction process used. Cattail fibres were manually decorticated from their leaves using a sharp knife which could have resulted to some micro-damages and thus compromising their strength. Furthermore, high cattail fibre breakages in treated hybrid composites may be attributed to their poor alkali treatment, since most of these extracted fibres were in bundles leading to poor impregnation of sodium hydroxide during treatment.

Improvement of flexural, tensile and compressive strengths as a result of alkali treatment, can be attributed to fibre strength improvement owing to alkali treatment (Table 4.3) and/or enhanced adhesion at the fibre/matrix interface. Enhanced fibre/matrix interface may be due to changes of surface topography of the fibres thus motivating increased mechanical interactions with the matrix as well as increasing fibre wettability by removal of all or some of the cementing components on the fibre surfaces such as lignin, fats and other surface impurities (Bichang'a et al., 2017; Gañan et al., 2005; Mwaikambo & Ansell, 1999) (Figure 4.13a-d). This trend is comparable to that reported by Alavudeen et al., (2011) working on improvement of mechanical properties by alkali treatment of randomly mixed banana/kenaf hybrid polyester composite where an increase of tensile strength by 14.1% from 31.90 MPa to 36.40 MPa at 50wt.% was reported. Senthilkumar and Ravi (2017) studied the effect of alkali treatment on flexural strength of sisal epoxy composites at 20wt.% and reported an improvement of flexural strength by 47.78% from 82.74 MPa to 122.27 MPa for untreated and 6% NaOH treated composites respectively.

4.3.3.2 Effect of Alkali treatment on flexural, tensile, compressive moduli of the hybrid composite at 15wt.% hybrid weight fraction and 50/50 sisal/cattail fibre content in the hybrid.

The findings on the effect of alkali treatment on flexural, tensile, compressive moduli of sisal/cattail hybrid polyester reinforced composite at a constant hybrid fibre weight fraction and percentage of sisal/cattail fibres in the hybrid of 15wt.% and 50/50 composition respectively were as shown in Figure 4.14.

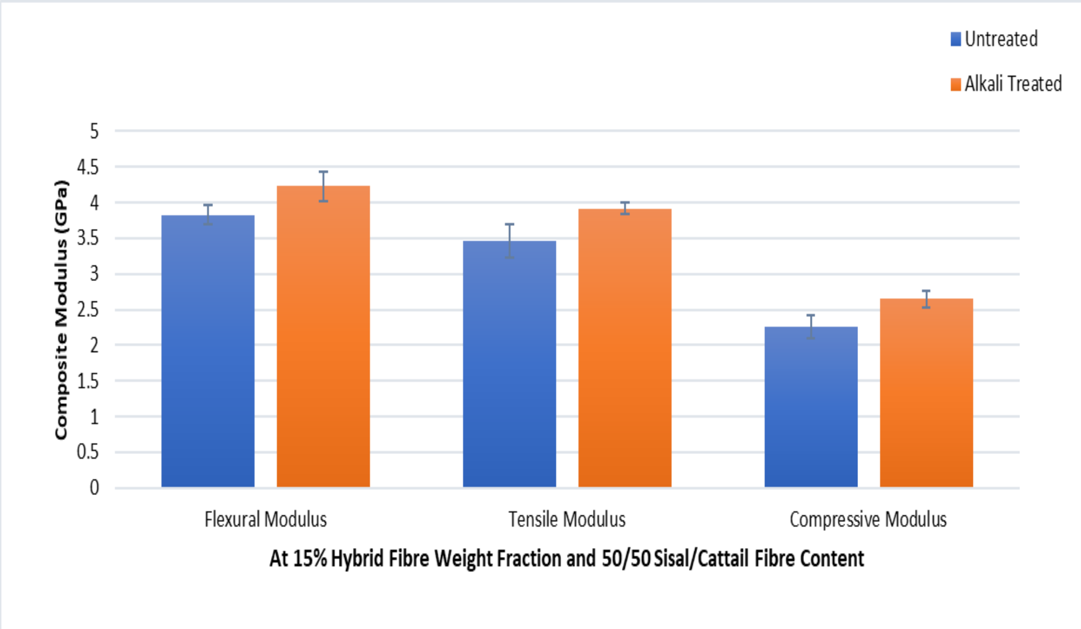


Figure 4.14: Effect of alkali treatment on flexural, tensile and compressive moduli of the hybrid composites at 15wt.% and 50/50 sisal/cattail content in the hybrid

It is evident from the analyzed results in Figure 4.14 that alkali treatment of sisal and cattail fibres resulted in an increase in flexural, tensile and compressive moduli of the hybrid composites. At 15wt.% and 50/50 sisal/cattail fibre content in the hybrid, flexural, tensile and compressive moduli increased by 10.44%, 12.97% and 17.26% respectively. Table 4.24 showed the calculated absolute T-values were higher than those of t-critical, suggesting a significance difference in means of flexural, tensile and compressive moduli of the treated and untreated hybrid composites. The *p*-values (two-tail) being less than

0.05 for flexural, tensile and compressive moduli indicates a rejection of the null hypothesis and thus acceptance of the alternative hypothesis.

Table 4.24: Paired T-test analysis for flexural, tensile and compressive moduli of sisal/cattail polyester composite

T-test Analysis-Flexural Moduli (GPa)			**T-test Analysis-Tensile Moduli (GPa)**			**T-test Analysis-Compressive Moduli (GPa)**		
	Untreated	Treated		Untreated	Treated		Untreated	Treated
Mean	3.83	4.23	Mean	3.47	3.9	Mean	2.26	2.65
Variance	0.024	0.052	Variance	0.068	0.01	Variance	0.11	0.017
Observations	5	5	Observations	5	5	Observations	5	5
Pearson Corr.	0.91		Pearson Corr.	0.98		Pearson Corr.	0.87	
H. Mean Dif.	0		H. Mean Dif.	0		H. Mean Dif.	0	
df	4		df	4		df	4	
t Stat	***-8.12***		t Stat	***-6.12***		t Stat	***-3.85***	
P(T<=t) one-tail	0.0006		P(T<=t) one-tail	0.002		P(T<=t) one-tail	0.009	
t Critical one-tail	2.13		t Critical one-tail	2.13		t Critical one-tail	2.13	
P(T<=t) two-tail	***0.0012***		P(T<=t) two-tail	***0.004***		P(T<=t) two-tail	***0.018***	
t Critical two-tail	***2.78***		t Critical two-tail	***2.78***		t Critical two-tail	***2.78***	

The aforementioned trend therefore is a clear indication that alkali treatment of sisal and cattail fibre reinforcement improved flexural, tensile and compressive moduli of the composites. This is because alkali treatment increased the surface roughness (exposure of the hydroxyl groups) to the matrix due to the removal of lignin and other impurities from the surface of the fibre thus improving fibre-matrix adhesion. Comparable pattern on the effect of alkali treatment on flexural, tensile and compressive modulus has been reported by previous researchers. Bichang'a et al. (2017) working on woven sisal reinforced epoxy composites reported an increase of flexural, tensile and compressive moduli of the composites by 12.97%, 31.19% and 34.98% after alkali treatment.

4.3.3.3 Effect of alkali treatment on impact strength of the hybrid composite at 15wt.% hybrid weight fraction and 50/50 sisal/cattail fibre content in the hybrid.

Figure 4.15 reveals the effect of alkali treatment on the impact strength of the hybrid composite at 15wt.% hybrid fibre loading and 50/50 percentage of sisal/cattail fibres in the hybrid.

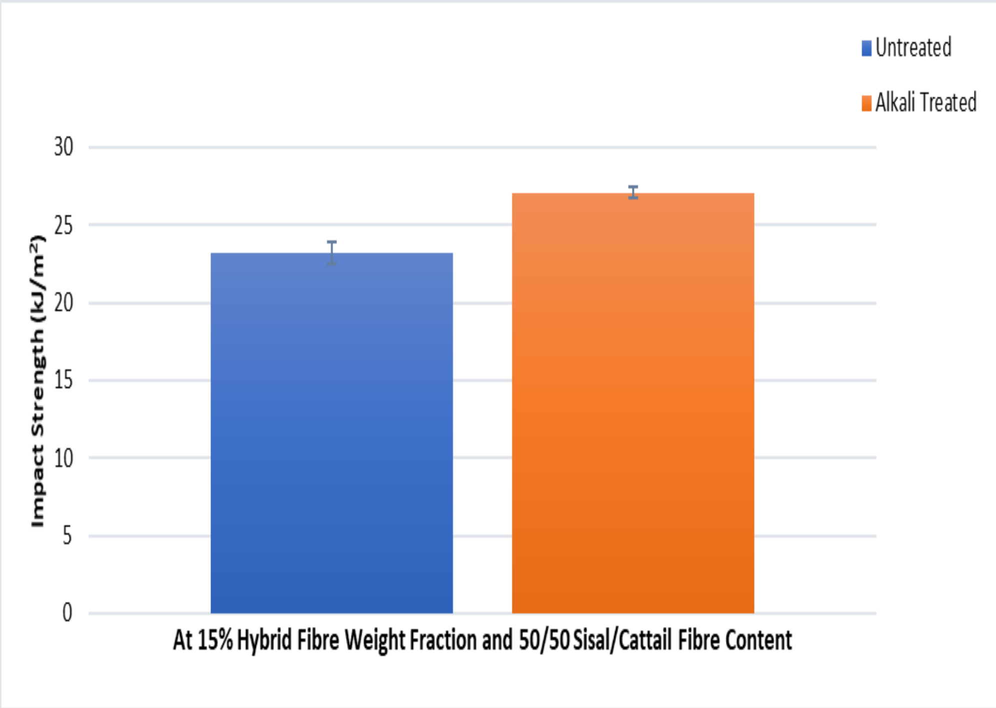


Figure 4.15: Effect of alkali treatment on impact strength of the hybrid composites at 15wt.% and 50/50 sisal/cattail content in the hybrid

Impact strength of the composites improved with alkali treatment of sisal/cattail fibre reinforcements by 16.77% to attain a value of 27.08 kJ/m^2. The computed absolute T-value for impact strength is higher than the two tailed t-critical value, suggesting a significant difference in impact strength between treated and untreated sisal/cattail polyester composites (Table 4.25). And since the value of P two-tail (0.0012) was less than the α-value ($P<0.05$), the probability that the obtained values are due to random chance are low, thus ascertaining a significance difference in impact strength between treated and untreated hybrid polyester composites.

Table 4.25: Paired T-test analysis for impact strength of sisal/cattail polyester composite

Indices	Untreated	Treated
Mean	23.19	27.08
Variance	0.60	0.13
Observations	5	5
Pearson Correlation	-0.67	
Hypothesized Mean Difference	0	
df	4	
t Stat	**-8.22**	
P(T<=t) one-tail	0.0006	
t Critical one-tail	2.13	
P(T<=t) two-tail	**0.0012**	
t Critical two-tail	**2.78**	

This difference in impact strength can be explained by increased energy required to break the specimen because of the strong fibre-matrix bonds created by exposing hydroxyl groups to the matrix due to the removal of lignin and other surface impurities by alkali treatment. Alavudeen et al. (2011) working on mechanical properties of randomly mixed banana/kenaf hybrid polyester composite reported an improvement of 24% impact strength from 0.50 kJ/m^2 to 0.62 kJ/m^2 untreated and alkali treated composites respectively at 30wt.% fibre weight fraction. Likewise, Bichang'a et al. (2017) reported an improvement of impact strength after alkali treatment of a woven sisal/epoxy composite. Failure mechanism was investigated by inspecting both treated and untreated impact specimens. It was found that the fracture surface of the untreated impact specimens was almost flat while that of treated specimens had saw-like fractured surfaces. Additionally, more fibre pull-outs were observed in untreated composite specimens and more fibre breakages in treated specimens. And therefore, the high values of impact strength reported earlier for treated hybrid composites may also be attributed to their failure modes (larger saw-like fractured surfaces and higher fibre breakages) as more impact energy is absorbed. Therefore, the major composite failure mode noted here was fibre pull-out (untreated) and fibre fracture (treated).

4.3.3.4 Effect of alkali treatment on Thermal Conductivity of the hybrid composite at 15% hybrid weight fraction and 50/50 sisal/cattail fibre content.

Table 4.26 summarizes the thermal conductivity properties of alkali treated and untreated hybrid composites with a constant fibre blend ratio of 50/50 (sisal/cattail) and a constant hybrid fibre weight fraction of 15wt %.

Table 4.26: Thermal conductivity properties of alkali treated and untreated sisal/cattail hybrid polyester composite at 50/50 sisal/cattail in the hybrid and 15wt.%.

	% of sisal and cattail in the hybrid	**Thermal Conductivity, λ (W/mK)**
Alkali Treated	50/50	0.7186(0.059)
Untreated	50/50	0.6595(0.046)

[a] Values in parentheses are standard deviations

The results of the effect of alkali treatment on thermal conductivity properties of sisal/cattail hybrid reinforced polyester composite are as shown in Figure 4.16.

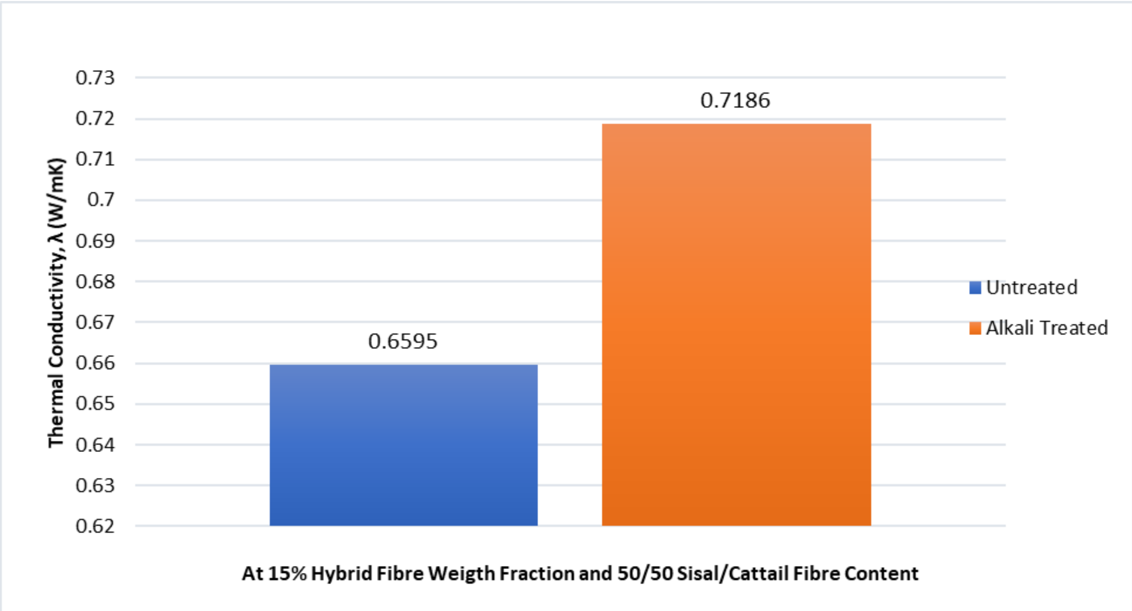


Figure 4.16**:** Effect of alkali treatment on thermal conductivity properties of the hybrid composites at 15wt.% and 50/50 sisal/cattail content in the hybrid

Thermal conductivity of the composites improved by 8.96% with alkali treatment. T-analysis gave a P-value of 0.062 which was higher than the alpha value ($P<0.05$) indicating an acceptance of null hypothesis and therefore suggesting that there was no significant difference between treated and untreated composites and this could have been due to systemic and random errors of the measurement. It was expected that alkali treatment should improve thermal conductivity significantly due to the removal of cementing materials from the fibre surfaces (destruction of aerenchyma tissues within the fibres especially cattail fibres) and thus reducing the thermal contact resistance of the resultant composite (Figure 4.18b). Reduction in fibre diameter results to better interlocking between the fibres and the matrix and therefore improving the thermal conductivity of the composite (Agrawal et al., 1999).

4.3.4 Effect of Hybrid Fibre Weight Fraction and Percentage of Sisal/Cattail Fibres in the Hybrid on the Thermal Conductivity Properties of the Composites

Table 4.27 summarises the thermal conductivity properties and density of sisal/cattail hybrid UPR reinforced composite at a constant percentage of sisal/cattail fibres in the hybrid and varying wt.%.

Table 4.27: Thermal conductivity properties and density of sisal/cattail hybrid polyester composite at 50/50 sisal/cattail percentages in the hybrid and at different hybrid fibre weight loading (wt.%)

Hybrid fibre weight fractions (wt.%)	Density (kg/m^3)	Thermal Conductivity, λ (W/mK)
5	1264.13	0.887(0.040)
10	721.68	0.861(0.045)
15	489.00	0.659(0.046)
20	480.24	0.631(0.013)
25	441.97	0.502(0.040)

[a] Values in parentheses are standard deviations

Table 4.28 below displays the results on the effect of varying the percentages of sisal/cattail fibre content in the hybrid on thermal conductivity properties of the hybrid composites.

Table 4.28: Thermal conductivity properties of sisal/cattail hybrid polyester composite at 15wt.% fibre loading and different percentages of sisal/cattail fibres in the hybrid

% of sisal/cattail in the hybrid	Thermal Conductivity, λ (W/mK)
0/100	0.309(0.090)
25/75	0.385(0.046)
50/50	0.659(0.046)
75/25	0.534(0.086)
100/0	0.558(0.128)

[a] Values in parentheses are standard deviations

4.3.4.1 Effect of varying the hybrid fibre weight fraction at a constant percentage of 50/50 sisal/cattail fibres in the hybrid on the thermal conductivity properties of the composites

The results of the effect of varying hybrid fibre weight fraction while the percentage of sisal/cattail fibres in the hybrid are kept at 50/50 is illustrated in Figure 4.17.

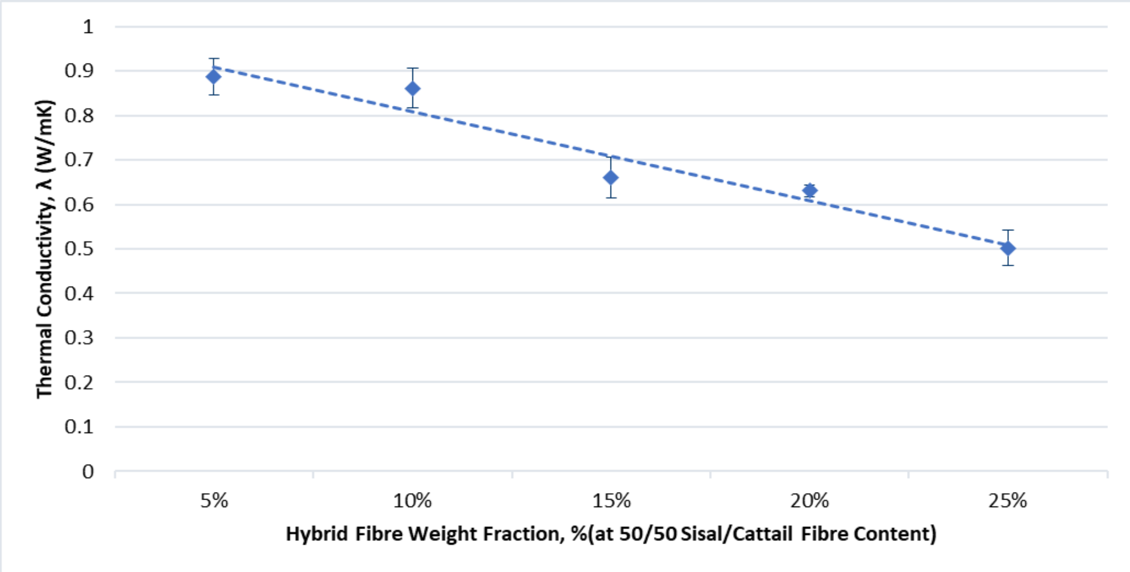


Figure 4.17: Effect of varying the hybrid fibre weight fraction on thermal conductivity properties of the composites at a constant percentage of 50/50 sisal/cattail fibres in the hybrid

Thermal conductivity of the hybrid composites decreased as the hybrid fibre loading increased from 5-25wt.% to attain a minimum thermal conductivity value of 0.502 W/mK (Figure 4.17). The thermal conductivity of the hybrid composites decreased by 2.93%, 23.4%, 4.31% and 20.39% for 5-10wt.%, 10-15wt.%, 15-20wt.% and 20-25wt.% hybrid fibre loadings respectively.

Table 4.29: Analysis of Variance for thermal conductivity properties of composites with varying hybrid fibre weight fraction and 50/50 sisal/cattail fibres in the hybrid

ANOVA						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F critical**
Between Groups	0.317308	4	0.079327	**10.79722**	0.001189	**3.47805**
Within Groups	0.07347	10	0.007347			
Total	0.390778	14				

As shown, ANOVA's F-calculated values were noted to be higher than F-critical values, suggesting a significant difference between the means of various composites at different hybrid fibre weight loadings. Furthermore, the value of P (0.001) was less than the alpha value ($P<0.05$) thus rejecting the null hypothesis.

The trend may be due to the presence of cattail fibres in the hybrid as well as their increment in the composite as hybrid fibre weight fraction increased from 5wt.% to 25wt.%; cattail fibres have lower thermal conductivity due to the presence of aerenchyma tissues (Figure 4.18a). Similar findings were reported. Ramanaiah et al., (2013) studying the effect of fibre weight fraction on thermal conductivity of fish tail palm tree fibre reinforced polyester composites reported a decrement in the thermal conductivity with increase in fibre content from 0.1 to 0.4 fibre volume fractions. A similar behaviour with increase in fibre loading was reported by Ramanaiah et al., (2011). Thermal insulation properties reported in the current study (at 25wt.%) were found to be better than those reported by Colbers et al. (2017) researching on the possibility of using cattail fibres in the production of insulation materials.

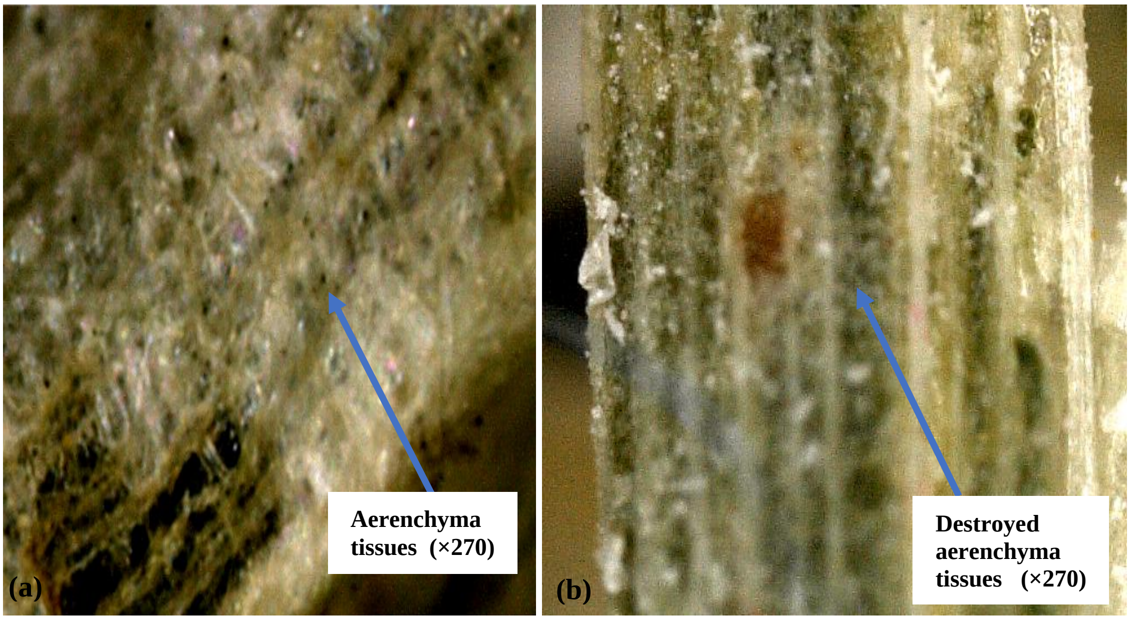


Figure 4.18: Micrographs of (a) untreated, and (b) alkali treated cattail fibres

4.3.4.2 Effect of hybrid composite density on thermal conductivity properties of the composite at a constant percentage of sisal/cattail fibres in the hybrid

The effect of composite density on thermal conductivity of the hybrid composite at 50/50 sisal/cattail fibre content in the hybrid are shown in Figure 4.19.

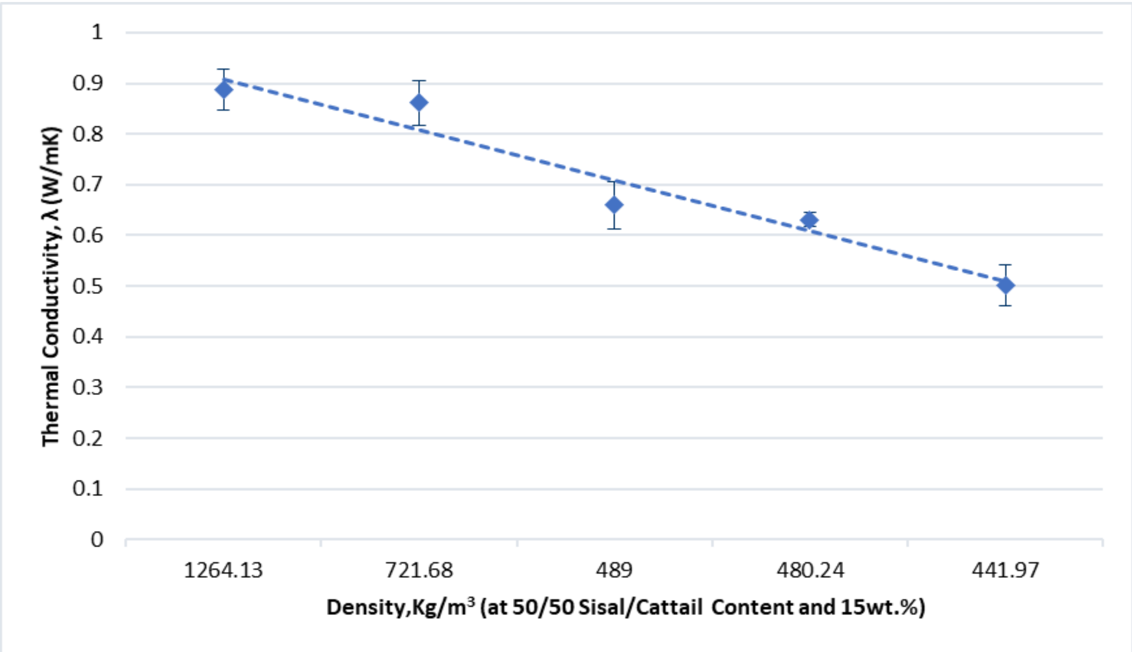


Figure 4.19: Effect of hybrid composite density on thermal conductivity properties of the composites at 50/50 sisal/cattail fibre content in the hybrid

Thermal conductivity is directly proportional to the hybrid composite density i.e. at high composite density, high thermal conductivity values were reported. This may be because as the density of the hybrid composite decreases, available voids between the fibres in the composite increases. It is these air-filled voids that result into lower thermal conductivity of the hybrid composite (Luamkanchanaphan et al., 2012). The same behaviour was reported by Sair et al. (2018) investigating the effect of density on thermal conductivity properties of hemp/polyurethane composite.

4.3.4.3 Effect of varying percentage of sisal/cattail fibres in the hybrid at a constant hybrid fibre weight fraction of 15wt.% on thermal conductivity of the composites

Figure 4.20 shows the effect of varying the percentage of sisal/cattail fibres at a constant hybrid fibre weight fraction of 15wt.% on the thermal conductivity of the composites.

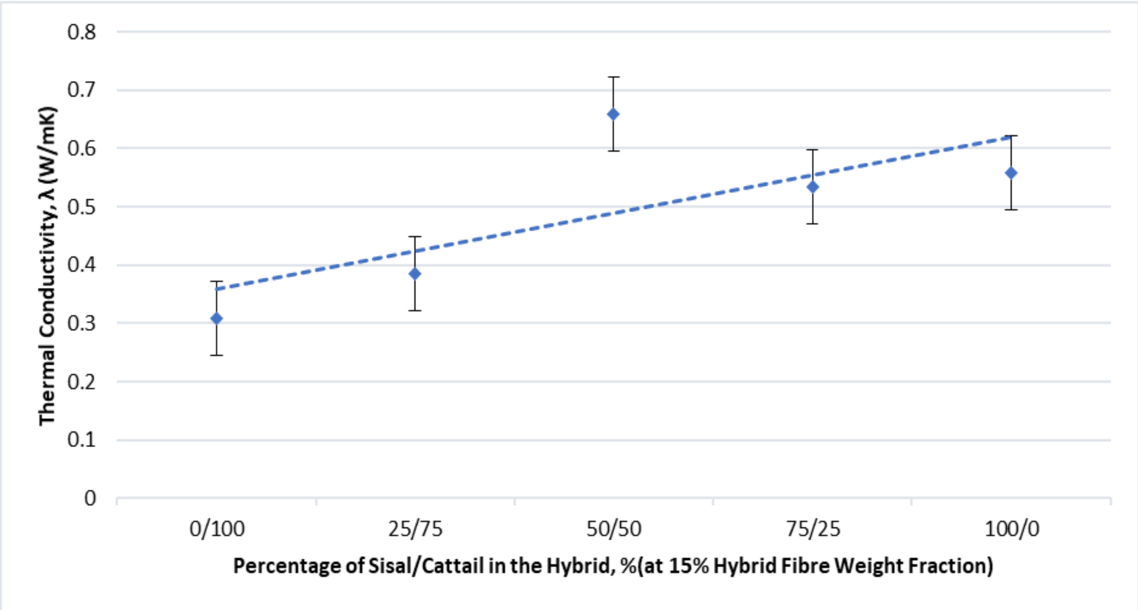


Figure 4.20: Effect of varying the percentage of sisal/cattail fibres in the hybrid on thermal conductivity of the composites at 15wt.%

Thermal conductivity of the hybrid composites increased with increase in the percentage of sisal fibres from 0-100% as the cattail fibre content decreased (100-0%). Low thermal conductivity value of 0.31 W/mK was reported at 0/100 sisal/cattail blend, while high thermal conductivity value of 0.56 W/mK was reported at 100/0 sisal/cattail fibre blend.

Table 4.30: Analysis of Variance for thermal conductivity properties of composites with varying percentages of sisal/cattail in the hybrid at 15wt.% hybrid fibre weight loading

ANOVA						
Source of Variation	**SS**	**df**	**MS**	**F**	**P-value**	**F critical**
Between Groups	0.237347	4	0.059337	**4.56989**	0.023398	**3.47805**
Within Groups	0.129843	10	0.012984			
Total	0.367189	14				

Thermal conductivities of the various composites fabricated by varying sisal/cattail volume ratios in the hybrid were significantly different since F-calculated value was higher than F-critical and P-value was less than 0.05 as shown in Table 4.30.

The results found in this work was consistent with previous studies; Alsina et al., (2005) reported thermal conductivity of 0.19-0.24 W/mK and 0.19-0.22 W/mK for jute/cotton hybrid polyester composites and ramie/cotton hybrid polyester composites respectively. Furthermore, Ramanaiah et al. (2011) studying thermal conductivity behaviour of cattail reinforced polyester composites reported a similar trend with thermal conductivity of 0.32-0.39 W/mK at a fibre volume fraction of 0.15-0.32. Close thermal conductivity values of 0.16 W/mK at 85% clay were reported by Dieye et al., (2017) who investigated the effect of clay (binder) weight on the mechanical and thermal properties of *Typha australis* fibre-reinforced composites.

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This study evaluated the mechanical (i.e. flexural, tensile, compressive and impact) and thermal properties of a hybrid composite manufactured from unsaturated polyester reinforced with a blend of sisal and cattail fibres. Three sets of composites were produced using a consolidation pressure of 3.27 kN/m^2. In the first set, a constant fibre blend ratio of 1:1 was used while the fibre weight fraction was raised from 5% to 25%. In the second set, a constant fibre weight fraction of 15% was used while the sisal to cattail blend ratio was varied from 0% to 100%. In the third set, a constant fibre weight fraction of 15% and a constant fibre blend ratio of 1:1 was used with treated fibres. From this work, the following conclusions were drawn:

a) Higher mean linear densities (26.17 tex and 35.17 tex) were recorded for untreated sisal and cattail fibres as compared to 10 tex and 12.33 tex recorded in the alkali treated fibres. The mean tenacity of treated sisal and cattail fibres were 146.26 cN/tex and 35.35 cN/tex compared to 23.52 cN/tex and 9.46 cN/tex recorded in the untreated fibres respectively.

b) Hybrid composite produced at constant fibre blend ratio of 1:1 have:

   - Optimal flexural, tensile, impact and compressive strengths at a fibre weight fraction of 20%.
   - A density that is directly proportional to its thermal conductivity.
   - Low thermal conductivity at a fibre weight fraction of 25%.

c) Hybrid composite produced at constant fibre weight fraction of 15% have:

- Optimal flexural, tensile, and compressive strengths at a sisal to cattail blend ratio of 3:1. However, impact strength increase with the sisal content in the blend.
- Higher flexural, tensile and compressive strengths as compared to those of unhybridized cattail/polyester composites.
- Low thermal conductivity as the proportion of sisal decrease to 0% and that of cattail increase to 100%.

d) Hybrid composite produced with treated fibres at constant fibre blend ratio of 1:1 and 15% fibre weight fraction have:

- Better mechanical properties (i.e. flexural, tensile, compressive and impact strengths) than similar hybrid composites produced from untreated fibres.
- Marginal improvement in thermal conductivity with alkali treatment.

e) Failure mechanism of sisal/cattail hybrid composites in this work occurred due to both fibre-pull-outs (mainly sisal fibres) and fibre fracture (mainly cattail fibres and partly sisal fibres).

5.2 Recommendations

a) Good mechanical and thermal conductivity properties presented in this work, reveals that, the resultant composite can be used for non-structural applications such as ceiling boards, electronic and food packaging. This therefore, calls for further studies on their physical properties such as water absorption, burning test, and flammability.

b) Cattail fibre extraction in this work was done by manual decortication process, using a knife, a process that was highly time consuming. Mechanisation of this process is highly recommended.

c) Since randomly oriented sisal/cattail fibres (15mm length) have been used in this study, other forms of these reinforcements such as woven cattail fabric have been recommended for future study.

REFERENCES

Agrawal, R., Saxena, N. S., Sreekala, M. S., & Thomas, S. (1999). Effect of Treatment on the Thermal Conductivity and Thermal Diffusivity of Oil-Palm-Fiber-Reinforced Phenolformaldehyde Composites. *Journal of Polymer Science*, *38*, 916–921.

Akash, Rao, K. V. S., Gupta, N. S. V., & S, A. kumar D. (2016). Mechanical Properties of Sisal/Coir Fiber Reinforced Hybrid Composites Fabricated by Cold Pressing Method. *IOP Conference Series: Materials Science and Engineering*, *149*(1). https://doi.org/10.1088/1757-899X/149/1/012092

Akil, H. M., Omar, M. F., Mazuki, A. A. M., Safiee, S., Ishak, Z. A. M., & Abu Bakar, A. (2011). Kenaf fiber reinforced composites: A review. *Materials and Design*, *32*(8–9), 4107–4121. https://doi.org/10.1016/j.matdes.2011.04.008

Alavudeen, A., Venkateshwaran, N., Elayaperumal, A., & Athijayamani, A. (2011). Improving Mechanical Properties of Eco-Friendly Polymer Hybrid Composites. *International Journal of Performability Engineering*, *7*(2), 172–178.

Alsina, O. L. S., Carvalho, L. H. De, Filho, F. G. R., & Almeida, J. R. M. (2005). Thermal properties of hybrid lignocellulosic fabric-reinforced polyester matrix composites. *Polymer Testing*, *24*, 81–85. https://doi.org/10.1016/j.polymertesting.2004.07.005

Asdrubali, F., D'Alessandro, F., & Schiavoni, S. (2015). A review of unconventional sustainable building insulation materials. *Sustainable Materials and Technologies*, *4*, 1–17. https://doi.org/10.1016/j.susmat.2015.05.002

Athijayamani, A., Thiruchitrambalam, M., Manikandan, V., & Pazhanivel, B. (2010). Mechanical properties of natural fibers reinforced polyester hybrid composite. *International Journal of Plastics Technology*, *14*(1), 104–116. https://doi.org/10.1007/s12588-009-0016-0

Bajwa, D. S., Sitz, E. D., Bajwa, S. G., & Barnick, A. R. (2015). Evaluation of cattail (Typha spp.) for manufacturing composite panels. *Industrial Crops and Products*, *75*, 195–199. https://doi.org/10.1016/j.indcrop.2015.06.029

Bichang'a, D. O., & Ayub, H. R. (2017). Effect of Fibre Weight Fraction on Mechanical Properties of Woven Sisal Fabric Reinforced Epoxy Composites. *International Journal of Engineering Science Invention*, *6*(11), 72–75.

Bichang'a, D. O., Wambua, P. M., & Oyondi, E. N. (2017). The effect of alkali treatment on the mechanical properties of sisal fiber reinforced epoxy composites. *American Journal of Engineering Research*, *4*(3), 31–39. https://doi.org/10.1177/0021998316646168

Bledzki, A. K., & Gassan, J. (1999). Composites reinforced with cellulose based fibres. *Progress in Polymer Science*, *24*, 221–274.

Cao, S., Dong, T., Xu, G., & Wang, F. (2016). Study on structure and wetting characteristic of cattail fibers as natural materials for oil sorption. *Environmental Technology (United Kingdom)*, *37*(24), 3193–3199. https://doi.org/10.1080/09593330.2016.1181111

Chakma, K., Cicek, N., & Rahman, M. (2017). Fiber extraction efficiency, quality and characterization of cattail fibres for textile applications. In *Session 4A: Bio-Fibre and Biomaterials: Production and Characterization* (pp. CSBE17-025). Winnipeg:

Canadian Society for Bioengineering. Retrieved from http://www.csbe-scgab.ca/docs/meetings/2017/CSBE17025.pdf

Colbers, B., Cornelis, S., Geraets, E., Gutiérrez-Valdés, N., Tran, L. M., Moreno-Giménez, E., & Ramírez-Gaona, M. (2017). A Feasibility Study on the Usage of Cattail (Typha Spp.) for the Production of Insulation Materials and Bio-adhesives. Retrieved from http://edepot.wur.nl/429929

Committee on Commodity Problems Joint Meeting of the Thirty-Ninth Session of the Forty-First Session of the Intergovernmental Group. (2017).

Cyras, V. P., Vallo, C., Kenny, J. M., & Vázquez, A. (2004). Effect of chemical treatment on the mechanical properties of starch-based blends reinforced with sisal fibre. *Journal of Composite Materials*, *38*(16), 1387–1399. https://doi.org/10.1177/0021998304042738

Dedeepya, M., Raju, T. D., & Kumar, T. J. (2012). Effect of Alkaline Treatment on Mechanical and Thermal Properties of Typha Angustifolia Fiber Reinforced Composites. *International Journal of Mechanical and Industrial Engineering (IJMIE)*, *1*(4), 2231 –6477.

Dieye, Y., Sambou, V., Faye, M., Thiam, A., & Adj, M. (2017). Thermo-mechanical characterization of a building material based on Typha Australis. *Journal of Building Engineering*, *9*, 142–146. https://doi.org/10.1016/j.jobe.2016.12.007

Frollini, E., Bartolucci, N., Sisti, L., & Celli, A. (2013). Poly(butylene succinate) reinforced with different lignocellulosic fibers. *Industrial Crops and Products*, *45*, 160–169. https://doi.org/10.1016/j.indcrop.2012.12.013

Gañan, P., Garbizu, S., Llano-Ponte, R., & Mondragon, I. (2005). Surface Modification of Sisal Fibers : Effects on the Mechanical and Thermal Properties of Their Epoxy. *Wiley InterScience*, (1). https://doi.org/10.1002/pc.20083

Gupta, G., Gupta, A., Dhanola, A., & Raturi, A. (2016). Mechanical behavior of glass fiber polyester hybrid composite filled with natural fillers. *IOP Conference Series: Materials Science and Engineering*, *149*(1). https://doi.org/10.1088/1757-899X/149/1/012091

Gupta, N. S. V., Akash, Rao, K. V. S., & S, A. kumar D. (2016). Fabrication and evaluation of mechanical properties of alkaline treated sisal/hemp fiber reinforced hybrid composite. *IOP Conf. Series: Materials Science and Engineering*, *149*(1). https://doi.org/10.1088/1757-899X/149/1/012093

Idicula, M., Joseph, K., & Thomas, S. (2010). Mechanical performance of short banana/sisal hybrid fiber reinforced polyester composites. *Journal of Reinforced Plastics and Composites*, *29*(1), 12–29. https://doi.org/10.1177/0731684408095033

Idicula, M., Malhotra, S. K., Joseph, K., & Thomas, S. (2005). Effect of layering pattern on dynamic mechanical properties of randomly oriented short banana/sisal hybrid fiber-reinforced polyester composites. *Journal of Applied Polymer Science*, *97*(5), 2168–2174. https://doi.org/10.1002/app.21980

Joseph, P., Mathew, G., Joseph, K., Groeninckx, G., & Thomas, S. (2003). Dynamic mechanical properties of short sisal fibre reinforced polypropylene composites. *Composites Part A Applied Science and Manufacturing*, *34*, 275–290. https://doi.org/10.1016/S1359-835X(02)00020-9

Joseph, P. V, Joseph, K., & Thomas, S. (1999). Effect of processing variables on the mechanical properties of sisal-fiber-reinforced polypropylene composites. *Composites Science and Technology*, *59*, 1625–1640.

Krus, M., Theuerkorn, W., Großkinsky, T., & Künzel, H. (2014). New sustainable and insulating building material made of cattail. *Nordic Symposium on Building Physics (NSB) <10, 2014, Lund>*, (156), 1252–1260. Retrieved from http://publica.fraunhofer.de/documents/N-323927.html

Liu, J., Zhang, Z., Yu, Z., Liang, Y., Li, X., & Ren, L. (2017). The Structure and Flexural Properties of Typha Leaves. *Applied Bionics and Biomechanics*, *2017*. https://doi.org/10.1155/2017/1249870

Liu, L., Chen, Y., & Zhu, J. (2013). New Development of Cattail Fibre in Composite Uses. *Advanced Materials Research*, *746*, 385–389. https://doi.org/10.4028/www.scientific.net/AMR.746.385

Luamkanchanaphan, T., Chotikaprakhan, S., & Jarusombati, S. (2012). A Study of Physical, Mechanical and Thermal Properties for Thermal Insulation from Narrow-leaved Cattail Fibers. *APCBEE Procedia*, *1*(January), 46–52. https://doi.org/10.1016/j.apcbee.2012.03.009

Mahato, K., Goswami, S., & Ambarkar, A. (2014). Morphology and Mechanical Properties of Sisal Fibre / Vinyl Ester Composites. *Fibres and Polymers*, *15*(6), 1310–1320. https://doi.org/10.1007/s12221-014-1310-9

Mancinoa, A., Marannano, G., & Zuccarello, B. (2018). Implementation of eco-sustainable biocomposite materials reinforced by optimized agave fibers. *Procedia Structural Integrity*, *8*(2017), 526–538. https://doi.org/10.1016/j.prostr.2017.12.052

Moghaddam, M. K., & Mortazavi, S. M. (2016). Physical and Chemical Properties of Natural Fibers Extracted from Typha Australis Leaves. *Journal of Natural Fibers*, *13*(3), 353–361. https://doi.org/10.1080/15440478.2015.1029199

Mortazavi, S. M., & Moghaddam, M. K. (2010). An Analysis of Structure and Properties of a Natural Cellulosic Fiber (Leafiran). *Fibres and Polymers*, *11*(6), 877–882. https://doi.org/10.1007/s12221-010-0877-z

Mortazavi, Sayed Majid, & Moghadam, M. K. (2009). Introduction of a new vegetable fiber for textile application. *Journal of Applied Polymer Science*, *113*(5), 3307–3312. https://doi.org/10.1002/app.30301

Mukherjee, P. S., & Satyanarayana, K. G. (1984). Structure and properties of some vegetable fibres. *Journal of Materials Science*, *19*, 3925--3934.

Mwaikambo, L. Y., & Ansell, M. P. (1999). The effect of chemical treatment on the properties of hemp , sisal , jute and kapok for composite reinforcement. *Die Angewandte Makromolekulare Chemie*, *272*(4753), 108–116.

Narsaiah, J., & Phani, K. V. S. (2016). Tensile and Flexural Properties of Cat-Tail Fiber Reinforced Unsaturated Polyester Composite, (8), 28–32.

Naveen, J., Jawaid, M., Amuthakkannan, P., & Chandrasekar, M. (2019). *Mechanical and physical properties of sisal and hybrid sisal fiber-reinforced polymer composites*. Woodhead Publishing Series in Composites Science and Engineering. https://doi.org/10.1016/B978-0-08-102292-4.00021-7

Ondiek, W. O., Ngetha, H. T., Keraita, J. N., & Byiringiro, J. B. (2018). Investigating the Effect of Fiber Concentration and Fiber Size on Mechanical Properties of Rice Husk Fiber Reinforced Polyester Composites. *International Journal of Composite Materials*, *8*(5), 105–115. https://doi.org/10.5923/j.cmaterials.20180805.01

Phanice, W. T., Thomas, K., & N, N. L. (2016). Concentration of I 2 , Na , K , Mg and Fe 2 + in Soils , Plants , Ash and Salt Samples of Selected Areas of Western Kenya, *5*(4), 2186–2209.

Phologolo, T., Yu, C., Mwasiagi, J. I., Muya, N., & Lim, Z. F. (2012). Production and characterization of Kenyan sisal. *Asian Journal of Textile*, *2*(2), 17–25. https://doi.org/10.3923/ajt.2012.17.25

Pickering, K. L., Efendy, M. G. A., & Le, T. M. (2016). Composites : Part A A review of recent developments in natural fibre composites and their mechanical performance. *Composites Part A Applied Science and Manufacturing*, *83*, 98–112. https://doi.org/10.1016/j.compositesa.2015.08.038

Plagens, M. J. (2016). Kenya Natural History Guide, Plants, Typha capensis. *Http://Www.Ngkenya.Com/Flora/Typha.Html*.

Ramanaiah, K., Prasad, A. V. R., & Reddy, K. H. C. (2013). Mechanical and Thermo-Physical Properties of Fish Tail Palm Tree Natural Fiber–Reinforced Polyester Composites. *International Journal of Polymer Analysis and Characterization*, *18*, 126–136. https://doi.org/10.1080/1023666X.2013.747464

Ramanaiah, K., Ratna Prasad, A. V., & Hema Chandra Reddy, K. (2011). Mechanical properties and thermal conductivity of typha angustifolia natural fiber-reinforced polyester composites. *International Journal of Polymer Analysis and Characterization*, *16*(7), 496–503. https://doi.org/10.1080/1023666X.2011.598528

Ramesh, M., Palanikumar, K., & Reddy, K. H. (2013a). Comparative Evaluation on Properties of Hybrid Glass Fiber- Sisal / Jute Reinforced Epoxy Composites. *Procedia Engineering*, *51*(NUiCONE 2012), 745–750. https://doi.org/10.1016/j.proeng.2013.01.106

Ramesh, M., Palanikumar, K., & Reddy, K. H. (2013b). Mechanical property evaluation of sisal–jute–glass fiber reinforced polyester composites. *Composites: Part B*, *48*, 1–9. https://doi.org/10.1016/j.compositesb.2012.12.004

Reddy, S. S. K., & Hussain, S. P. A. (2013). Development and Testing of Natural Fiber Reinforced Composites with Polyester Resin. *International Journal of Engineering Sciences & Research Technology*, *2*(10), 2701–2706.

Rezig, S., Jaouadi, M., Khoffi, F., Msahli, S., & Durand, B. (2016). Optimization of extraction process of typha leaf fibres. *Indian Journal of Fibre and Textile Research*, *41*(3), 242–248.

Rizal, S., Ikramullah, Gopakumar, D. A., Huzni, S., Thalib, S., Syakir, M. I., … B, H. P. S. A. K. (2019). Tailoring the Effective Properties of Typha Fiber Reinforced Polymer Composite via Alkali Treatment. *BioResources*, *14*(3), 5630–5645.

Romão, C., Vieira, P., & Esteves, J. L. (2004). Mechanical Characterisation of Sisal Fibres for Reinforcing of Composite Materials with several different Surface Treatments. *11th European Conference on Composite Materials-ECCM11*, 3–8.

Sair, S., Oushabi, A., Kammouni, A., Tanane, O., Abboud, Y., & Bouari, A. El. (2018).

Mechanical and thermal conductivity properties of hemp fiber reinforced polyurethane composites. *Case Studies in Construction Materials*, *8*(January), 203–212. https://doi.org/10.1016/j.cscm.2018.02.001

Samuel, O. D., Agbo, S., & Adekanye, T. A. (2012). Assessing Mechanical Properties of Natural Fibre Reinforced Composites for Engineering Applications. *Journal of Minerals and Materials Characterization and Engineering*, *11*(08), 785–789. https://doi.org/10.4236/jmmce.2012.118067

Sana, R., Foued, K., Yosser, B. M., Mounir, J., Slah, M., & Bernard, D. (2015). Flexural Properties of Typha Natural Fiber-Reinforced Polyester Composites. *Fibers and Polymers*, *16*(11), 2451–2457. https://doi.org/10.1007/s12221-015-5306-x

Sana, R., Mounir, J., & Slah, M. (2014). Study of Structure and Properties of Tunisian Typha Leaf Fibers. *International Journal of Engineering Research & Technology (IJERT)*, *3*(3), 2278–0181.

Santhosh, J., Balanarasimman, N., Chandrasekar, R., & Raja, S. (2014). Study of Properties of Banana Fiber Reinforced Composites. *International Journal of Research in Engineering and Technology*, *3*(11), 144–150. Retrieved from http://www.ijret.org

Santos, F. M. dos, Batista, F. B., Panzera, T. H., Christoforo, A. L., & Rubio, J. C. C. (2017). Hybrid composites reinforced with short sisal fibres and micro ceramic particles. *Revistamaterial*, *22*(2).

Senthilkumar, K., Siva, I., Jappes, J. T. W., Amico, S. C., Cardona, F., & Sultan, M. T. H. (2016). Effect of inter-laminar fibre orientation on the tensile properties of sisal fibre reinforced polyester composites. *Materials Science and Engineering*, *152*(1). https://doi.org/10.1088/1757-899X/152/1/012055

Senthilkumar, P., & Ravi, S. (2017). The Effect of Alkali Treatment on the Mechanical Properties of Sisal Fiber Reinforced Epoxy Composites. *International Journal of Advanced Scientific Research & Development*, *04*(03), 31–39. Retrieved from http://www.ijasrd.org/in%0AInternational

Silva, F. de A., Chawla, N., & Filho, R. D. de T. (2008). Tensile behavior of high performance natural (sisal) fibers. *Composites Science and Technology*, *68*(15–16), 3438–3443. https://doi.org/10.1016/j.compscitech.2008.10.001

Sivasubramanian, P., Thiruchitrambalam, M., & R, S. (2013). Hybridization of Natural Fiber Composites on Mechanical Properties. *International Journal of Scientific & Engineering Research*.

Sojda, R. S., & Solberg, K. L. (1993). Management and Control of Cattails. In R. S. Sojda & K. L. Solberg (Eds.), *Waterfowl Management Handbook* (pp. 1–8). Minnesota: Diana H. Cross and Paul Vohs (eds.). Retrieved from http://digitalcommons.unl.edu/icwdmwfm

Teja, M. S., Ramana, M. V, Sriramulu, D., & Rao, C. J. (2016). Experimental Investigation of Mechanical and Thermal properties of sisal fibre reinforced composite and effect of sic filler material. *Materials Science and Engineering*, *149*. https://doi.org/10.1088/1757-899X/149/1/012095

Venkateshwaran, N., ElayaPerumal, A., Alavudeen, A., & Thiruchitrambalam, M. (2011). Mechanical and water absorption behaviour of banana/sisal reinforced hybrid composites. *Materials and Design*, *32*(7), 4017–4021. https://doi.org/10.1016/j.matdes.2011.03.002

Vimalanathan, P., Venkateshwaran, N., & Santhanam, V. (2016). Mechanical, dynamic mechanical, and thermal analysis of Shorea robusta-dispersed polyester composite. *International Journal of Polymer Analysis and Characterization*, *21*(4), 314–326. https://doi.org/10.1080/1023666X.2016.1155818

Wambua, P., Ivens, J., & Verpoest, I. (2003). Natural fibres : can they replace glass in fibre reinforced plastics ?, *63*, 1259–1264. https://doi.org/10.1016/S0266-3538(03)00096-4

Wuzella, G., Raj, A., Bätge, T., Jury, S., & Kandelbauer, A. (2011). Novel , binder-free fiber reinforced composites based on a renewable resource from the reed-like plant Typha sp ., *33*, 683–689. https://doi.org/10.1016/j.indcrop.2011.01.008