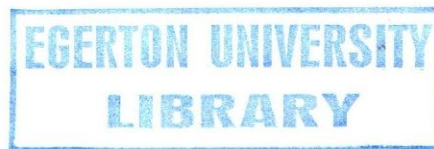


**DETERMINATION OF INFLUENCE OF NATURAL FIBERS ON
THE PROPERTIES OF FIBER REINFORCED POLYESTER
COMPOSITES**



Mutai Alice Jepkorir



**A Thesis submitted to the Graduate School in partial fulfillment for the
requirements of the Master of Science Degree in Engineering Systems and
Management of Egerton University.**

EGERTON UNIVERSITY

April, 2010



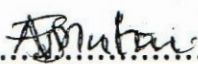
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DECLARATION

I declare that this thesis is my original work and that it has not been presented before to any other University for a similar or any other Degree award.

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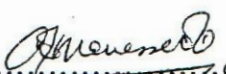
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I dedicate this study to my husband Daniel for his endless support and encouragement, my children Edward and Beth for their understanding and tons of love. My father Haron and mother Grace without forgetting my brothers and sister for providing me with all the opportunities and guidance.

To the Almighty Father, to whom I owe everything.

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Sisal and pineapple fibers can be used as environmentally friendly alternatives to conventional reinforcing fibers (e.g. glass) in composites. The interest in natural fiber-reinforced polymer composites is growing rapidly due to their high performance in terms of mechanical properties, significant processing advantages, excellent chemical resistance, low cost and low density. These advantages place natural fiber composites among the high performance composites having economic and environmental advantages. The composites from sisal and pineapple fibers would result in a product material that is partially biodegradable as well as add economic value to plants. On the other hand, lack of consistent data on the performance of these fiber composites and poor resistance to moisture absorption make the use of natural fiber-reinforced composites less attractive to manufacturers. This study aimed at determining the influence sisal and pineapple leaf fibers would have on the composite properties in comparison with corresponding properties of polyester reinforced composites from literature. Leaf fibers from sisal and pineapple plants, known for their relatively high cellulose contents were extracted, surface modified and used in the study. The composites were fabricated by both the hand layup and compression methods. Three-point bend and hardness tests were carried out in accordance to ASTM D790-03 and ASTM D2240-05 standards respectively. The sisal/Palf hybrid composites showed higher bending strength than the individual composites. It was observed that the addition of glass fibers into the plant fibers enhanced the composite properties. Water absorption and thickness swelling tests were conducted in accordance with ASTM D570-99 and ASTM D1037-03 standards respectively to determine their susceptibility to wet conditions because of the hygroscopic nature of natural fibers. These tests indicated that higher fiber contents resulted in higher water absorption with the composites having glass fibers registering the lowest water uptake. This suggested that incorporating glass fibers into the natural fibers improves both the mechanical and physical properties of the resulting composites. The study concluded that sisal and pineapple fibers both sourced from plant leaves produce composites with differing properties leading to differences in performance and industrial applications.

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LIST OF ABBREVIATIONS

ASTM	American Society for Testing of Materials
C.N.C	Computer Numeric Control machine
CSM	Chopped Strand Mats
FAO	Food Agricultural Organization
FRP	Fiber reinforced plastic
GRP	Glass reinforced plastic
GFRP	Glass fiber reinforced plastic
KEBS	Kenya Bureau of Standards
MEKP	Methyl ethyl ketone peroxide
PALF	Pineapple leaf fiber
PMC	Polymeric matrix composites
PP	Polypropylene
UP	Unsaturated polyester
UV	Ultra violet
VE	Vinyl ester

1.1 Background Information

Fiber reinforced composite materials are composed of fibers and a binder or a matrix that protects and binds together the fibrous reinforcements. The fibers are usually the load bearing members providing strength and rigidity, while the matrix maintains the position and orientation of the reinforcement (Taj *et al*, 2007).

Composites are defined as structures where two or more materials that are different in structure and properties are combined to form a single structure with identifiable interfaces and properties that are superior to those of its constituents (Hull and Clyne, 1996). A tree is a composite made of wood fiber held together by sap. Concrete is also a composite made of cement (binder), sand and gravel as reinforcement (Strong, 1996).

Fiber reinforced polymer (FRP) composites have been used as structural materials since World war II, when they were first used in the construction of the British Spitfires. They consist of stiff fibers of about 10 μ m diameter embedded in a thermoset or thermoplastic polymer matrix (Mirmiran *et al*, 2003).

Glass fiber reinforced plastic (GFRP) originally developed in the United Kingdom as a replacement for the molded plywood used in aircraft radomes gained acceptance in the boating industry in 1950's. Carbon fibers were introduced in the early 1960's and because of their comparative superior strength and stiffness properties soon became the fiber of choice for advanced composite applications in the aerospace industry. Today, these synthetic fibers are extensively used as reinforcement of plastics and now dominate the aerospace, leisure, automotive, construction and sporting industries with glass being the most widely used due to its low cost when compared to aramid and carbon and fairly good mechanical properties. Fiberglass composites are used extensively as metal replacements for automotive parts such as valves, covers, power steering reservoirs, fuel pumps, fan shrouds, spoilers and car pedals (Shaharuddin, *et al*, 2005). The challenge is to make them more cost effective (Mirmiran *et al*, 2003) so as to meet the ever changing need of revitalizing the infrastructure with innovative materials and structural systems that last longer and require less maintenance costs (Bakis *et al.*, 2002).

are posing challenges to researchers to replace the non-environmental friendly synthetic fiberglass with natural fibers (Mishra *et al*, 2004). Interest in natural fiber (lignocellulose fiber) composites for industrial applications has increased significantly in the recent years. According to Bledzki and Gassan (1999), Wambua *et al*. (2003) and Mishra *et al*. (2001), lignocellulose fibers offer several advantages over their synthetic fiber counterparts. Lignocellulose fibers are abundant in nature, renewable raw material and a low cost material. Owing to their low specific gravity, which is about 1.25-1.50 g/cm³ compared to synthetic fibers, and especially glass fiber which is about 2.6 g/cm³, lignocellulose fibers are able to provide a high strength to weight ratio in plastic materials. The usage of lignocellulose fibers also provides a healthier working condition than the synthetic fibers. This is due to the fact that, the glass fiber dust from the trimming and mounting of glass fiber components causes skin irritation and respiratory diseases among workers. Besides that, the less abrasive nature of the lignocellulose fibers offers a friendlier processing environment as the wear of tools could be reduced. Furthermore, lignocellulosic fibers offer good thermal and insulating properties, easily recyclable and are biodegradable especially when used as reinforcement in a biopolymer matrix. These advantages have gained interest in the automotive industry where materials of lightweight, high strength to weight ratio and minimum environmental impact are required. Automotive giants such as DaimlerChrysler are using flax/sisal fiber mat embedded in an epoxy matrix for the door panels of the Mercedes Benz E-class model (Gayer, 1996). Coconut fibers bonded with natural rubber latex are being used for seat cushions in the Mercedes Benz A-Class model (Schuh 2003). Cambridge Industry (an automotive industry in Michigan, USA) is making flax fiber reinforced polypropylene for Freightliner Century COE C-2 heavy trucks and also rear shelf trim panels of the 2000 model Chevrolet Impala (Sharman, 2004). Besides the automotive industry, lignocellulosic fiber composites such as jute fiber reinforced polyester have also found application in the building and construction industries such as panels, ceilings and partition board. However, lignocellulose fiber composite products are still limited to the interior of cars that are not exposed to strong mechanical impacts and non-structural components compared to synthetic fiber composites which are used widely in high

performance engineering applications such as in the aerospace industry. This is because lignocellulosic fiber composites have low strength properties, poor moisture resistance, poor microbial and fire resistance and low durability properties (Kathiresen, 2004). Therefore, through hybridization of the lignocellulosic fibers with a stronger and more corrosion resistant synthetic fiber such as glass fibers, the strength, stiffness, moisture and fire resistant behavior of the lignocellulosic composite can be improved significantly. The natural fiber composites can be very cost effective material for the following applications (Maschinenwesen, 2006):

- Building and construction industry: panels for partition and false ceiling, partition boards, wall, floor, window and door frames, roof tiles, mobile or pre-fabricated buildings which can be used in times of natural calamities such as floods, cyclones and earthquakes.
- Storage devises: post-boxes, grain storage silos and bio-gas containers.
- Furniture: chairs, tables, shower and bath units.
- Electric devises: electrical appliances and conduits.
- Everyday applications: lampshades, suitcases and helmets.
- Transportation: boat, automobile and railway coach interior.
- Toys

The reasons for the application of natural fibers in the automotive industry include low density leading to a weight reduction of 10 to 30%, acceptable mechanical properties with good acoustic properties and favourable processing properties resulting in low wear on tools. However, natural fiber composites possess some disadvantages. The main disadvantage is the poor compatibility between a hydrophobic polymer matrix and the hydrophilic fibers, which leads to the formation of weak interfaces that result in poor mechanical properties of the composites (Karus, 2000; Beckmann and Kleinholz, 1999).

1.2 Problem statement

Present-day research in the field of polymer science and technology focuses on newer materials and composites that have both economic and environmental benefits for application in the automotive, building and furniture industries. Manufacturers of fiber composite products in Kenya use the imported conventional glass fibers as the

reinforcing material. Fiberglass products now dominate the leisure, automotive, building and sporting industries with the cost of these materials on the upward trend. Environmental cost of manufacturing energy intensive synthetic fibers as well as the prevailing uncertainties in the supply and price of petroleum-based products generated interest in looking for alternative sources of fibers. Availability of inexpensive natural fibers such as sisal and pineapple leaf fibers (palf) provides the opportunity of exploring the possibility of their utilization for inexpensive composites for various applications. In order to develop and promote these natural fibers and their composites, it is necessary to understand their mechanical properties as they are intrinsically dependent on where they are grown (locality), what part of the plant they are harvested from, such as leaf, stem or fruit and the age of the plant at the time of harvest. The best reinforcement material ought to raise the mechanical properties and reduce the cost of the composites.

1.3 Objectives of the Study

The overall objective of this study was to compare the mechanical and physical properties of composites made from sisal, palf, sisal/palf, glass/sisal, and glass/palf fibers with corresponding properties of polyester reinforced composites from literature.

The specific objectives were to:

- (i) Determine bending strength, hardness values, water absorption and thickness swelling of composite samples from sisal, palf, sisal/palf, glass/sisal, and glass/palf fibers.
- (ii) Compare the results of the mechanical and physical properties obtained with that of polymer composite data from literature.

1.4 Justification

The use of sisal and pineapple leaf fibers have not had their potential application fully exploited as sisal fibers are presently used in making ropes, upholstery, padding, mat and fishing nets, fancy articles such as purses, wall hangings and table mats. Although sisal is a major fiber crop in Kenya, it is losing ground to synthetic materials. Pineapple leaves, on the other hand, become waste of agriculture after harvest of the fruits. These natural

fibers have the potential of supplementing and consequently replacing the extensively used synthetic fibers. Using sisal and pineapple fibers to make composites result in a cleaner environment as well as creating jobs and increased earnings to the farmers and the country at large. There is, therefore need for research on the performance of composites from these fibers in order to determine possible end uses.



LITERATURE REVIEW

2.1 Introduction

Fiber reinforced Plastics (FRP) or polymeric composites are formed by combining fibers and polymer resin. The term polymer refers to the long chain molecule that is composed of a large number of repeating units of identical structure. This covalent bonding is formed via polymerization process and can be linear in shape or even more complicated networking. Commonly, composites tend to have characteristics such as high strength, high modulus, low density and excellent resistance to fatigue, creep, creep rupture, corrosion and wear (Mokhtar *et al*, 2007). Glass, carbon, aramid, boron and cellulose fibers are widely used as reinforcement in composite materials. The FRP industry today is experiencing significant growth as more products are made from reinforced plastics for greater durability and strength. There are thousands of products that are manufactured from these plastics; building materials, sporting equipment, electrical appliances, automotive and aircraft parts, boat and canoe hulls and bodies for recreational vehicles (<http://www.p2pays.org/ref/32/31016.htm>, 2006). Use of composites is preferred whenever strength has to be combined with lightweight and durability (Bakis *et al*, 2000).

2.2 Fibers

A fiber is defined as a unit of matter characterized by flexibility, fineness and high ratio of length to thickness (Mwaikambo, 2006). Fibers are classified according to source; that is from animal, vegetable, mineral or synthetic origin, chemical structure or both. Commercially available fibers have diameters ranging from less than 0.004mm to 0.2mm and they come in several forms: short fibers (chopped), continuous single fibers and untwisted bundles of continuous filaments (yarns). They can be braided into ropes and cordage, made into fells (non-woven) or knitted into textile fabrics or in case of high-strength fibers used as reinforcements in composites (Encarta Encyclopedia, 2004: fiber). Fibers are very strong and rigid in tension. The reason is that the molecules in the fibers are oriented in the longitudinal direction, and their cross-sections are so small that there is a low probability that any defect exists in the fiber. Fiber reinforcement materials are added to the resin system to provide strength to the finished part. The selection of

reinforcement material is based on the properties desired in the finished product. These materials should not react with the resin but are an integral part of the composite (Vaidya, 2002).

Glass fibers, known for their strength, for example, can have tensile strengths as high as 4600 MPa (650Psi) whereas the strength of a glass in bulk form is much lower. Glass fibers are stronger than steel (Kalpakjian, 1995). Short fibers generally have an aspect ratio (the length to diameter ratio) between 20 and 60, and long fibers between 200 and 500 (Kalpakjian, 1995).

2.2.1 Glass fibers

Glass fibers are the most common of all reinforcing fibers for polymeric matrix composites (PMCs) and are used in 95 % of cases to reinforce thermoplastic and thermoset composites (Mohanty *et al*, 2005). The principal advantages of glass fibers are low cost and high strength, high chemical resistance and excellent insulating properties compared with others synthetic fibers. The disadvantages are low modulus of elasticity and poor adhesion to polymer matrix resins, particularly in the presence of moisture (Jusoh, 2008). The two types of glass fibers commonly used in the fiber reinforced plastics industries are E-glass and S-glass. E-Glass has good strength properties at low cost. It is used in circuit boards of computers to provide stiffness and high electrical resistance. Because of electrical resistance it is suited for applications where radio-signal transparency is desired as in aircraft radomes and antenna. It has a specific gravity of 2.54 g/cc and a melting point of 1555 °F (846 °C). Its refractive index is 1.547 (Vaidya, 2002). Another type known as C-glass is used in chemical applications requiring greater corrosion resistance to acids than is provided by E-glass (Taj, 2007).

Glass fibers are made by drawing molten glass through small openings in a platinum die. By impregnating glass fibers with resins, a composite fiberglass is formed that combines the strength of the inertness of glass with impact resistance of the plastics. Strong and stiff glass fibers carry loads imposed on the composite while the resin matrix spreads the load across the fibers. The strength and stiffness in the fiber glass/plastic composite are provided by glass fibers, which are extremely strong; their elasticity may be 50 times greater than that of the plastic (Encarta Encyclopedia, 2004: glass). The

strength of small diameter glass fibers is combined with the ductility of the polymeric matrix. The combinations of these two components provide products that are superior to either component alone (Shakelford, 1988). Studies indicate that the tensile strength of glass fiber reinforced polyester composites (10-16% glass fiber) as 26-41 MPa with Elastic modulus of 12.40 GPa (Mathur, 2006).

Studies on the strength characteristics of polyester resin composites containing glass and carbon as reinforcing materials conclude that glass strands as reinforcement significantly increased stiffness and strength over resin alone. Carbon fibers in equivalent volumes increased this even more. Figures 2.1 and 2.2 show the average stiffness and strength values for the different samples tested. They also showed that both reinforcing materials increased sample strength to various degrees depending on their percent of fills as shown in Figure. 2.2. The charts of stiffness and strength showed that doubling the reinforcement volume fill does not double the strength of the sample.

2.3 Current Trend of Composite

In this new era of technology, availability of bio-based composites offer the opportunity for environmental gains, reduced energy consumption, light weight, insulation and sound absorption properties, reduction in volatile organic emissions and reduction in the dependence on petroleum based and forest product based materials. The development of sustainable materials as an alternative for petroleum based materials is being studied to decrease the dependence on oil or petroleum. This also can reduce carbon dioxide emissions and to generate a more economic opportunity for the agricultural sector globally.

2.4 Natural fibers

Natural fibers, as reinforcement in petroleum-based resins, have in the recent past attracted the attention of researchers because of their advantages over other conventional reinforcing materials.

AVERAGE STIFFNESS OF TEST COUPONS

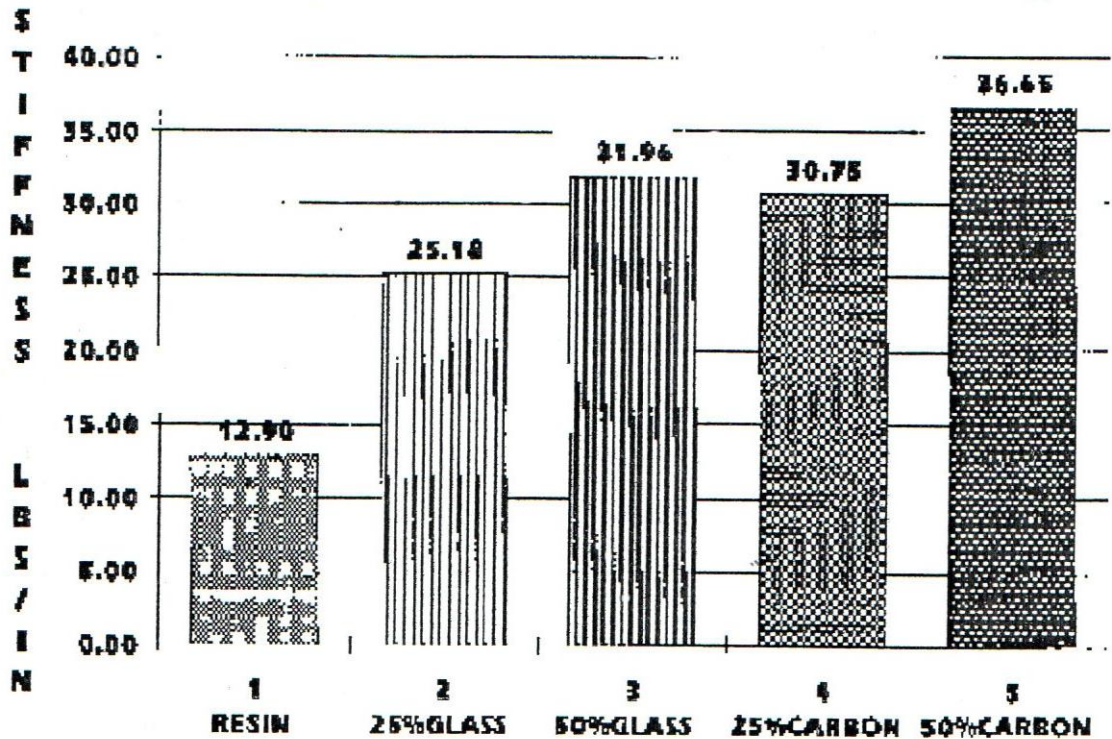


Figure 2.1 The average stiffness values for the different coupons

Source: <http://www.bc.bangor.ac.uk/suscomp/inder.htm> (2003)

Standard deviation of measured stiffness values for all tests averaged 8%. Standard deviation of failure strengths derived from the test data averaged 17%.

These advantages include low cost, low density as shown in Table 2.1, acceptable specific properties, reduced health hazards and reduced wear on processing machinery, enhanced energy recovery and biodegradability (Mokhtar *et al*, 2007). These fibers are also abundantly available, renewable, cheaper than conventional fibers (Mohanty *et al*, 2002) and are environmentally friendly as they are fully biodegradable (Mwithiga and Mwanja, 2006). The biodegradability of plant fibers can contribute to a healthy ecosystem while their low cost and high performance fulfils the economic interest of industry.

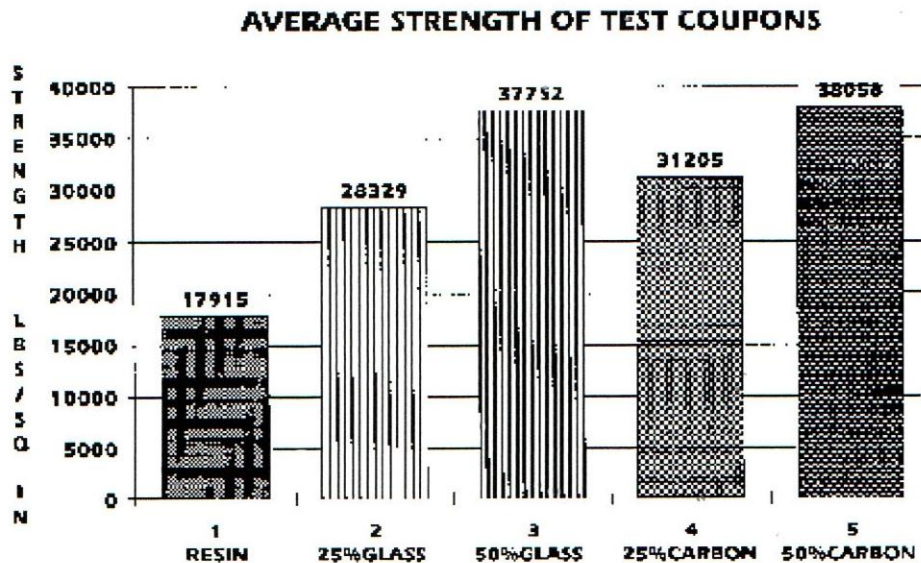


Figure 2.2 The average strength values for the various test coupons

Source: <http://www.bc.bangor.ac.uk/suscomp/inder.htm> (2003)

When natural fiber reinforced plastics are subjected, at the end of their life cycle, to combustion process or landfill, the released amount of carbon-dioxide (CO_2) from the fibers is neutral with respect to the assimilated amount during their growth (Eichhorn *et al*, 2001). Although natural fibers and their composites are environmental-friendly and renewable (unlike traditional sources of energy, i.e., coal, oil and gas), these have several bottlenecks. They have poor wettability, high moisture absorption and are incompatible with some polymeric matrices (Hon and Shiraishi, 2001). This reduces their potential as reinforcing materials due to the significant effect in the mechanical properties of the composites (Stamboulis *et al*, 2001 and Chow, 2003). Tensile properties of natural fiber composites with a high fiber fraction can decrease up to 65 % after immersion in water for 24 hours. In order to improve the adhesion between the fiber and the matrix for both thermoplastic and thermoset compounds and to reduce the water absorption (Bledzki, 1996) compatibilizing agents or surface treatment of the fibers is done prior to composite

microfibrils in an amorphous matrix of 60-80% hemicellulose, 5-20% lignin and up to 20% moisture. The hydrogen bonds and other linkages provide the necessary strength and stiffness to the fiber (Kandachar, 2002).

Table 2.1 Comparative properties of natural fibers and conventional man-made fibers.

Fiber	Fiber Density (g/cm ³)	Diameter (μm)	Tensile Strength (MPa)	Young's Modulus (GPa)	Elongation at Break (%)
Jute	1.3-1.45	20-200	393-773	13-26.5	7-8
Flax	1.5	-	345-1100	27.6	2.7-3.2
Hemp	-	-	690	-	1.6
Ramie	1.5	-	400-938	61.4-128	1.2-3.8
Sisal	1.45	50-200	468-640	9.4-22	3-7
Palf	-	20-80	413-1627	34.5-82.51	1.6
Cotton	1.5-1.6	-	287-800	5.5-12.6	7-8
Coir	1.15	100-450	131-175	4-6	15-40
E-glass	2.5	-	2000-3500	70	2.5
S-glass	2.5	-	4570	86	2.8
Aramid	1.4	-	3000-3150	63-67	3.3-3.7
Carbon	1.7	-	4000	230-240	1.4-1.8

Source: Maschinenwesen (2006)

2.4.1 Classification of plant fibers

Natural fibers are sub-divided based on their origins: derived from plants, animals or minerals. Plant or vegetable fibers are generally used to reinforce plastics with at least 1000 types of plants in existence bearing usable fibers (Robson *et al*, 1993). Natural fibers are strong but light in weight, non-hazardous to health and inexpensive. These abundantly available fibers are in general, suitable to reinforce plastics due to their relative high strength, stiffness and low density (Bledzki and Gassan, 1999), and since these fibers have small cross-sections and cannot be directly used in engineering applications, they are embedded in matrix materials to form fiber composites. Cotton-polymer composites are reported to be the first fiber reinforced plastics used (Piggot, 1980; Lubin, 1982).

Vegetable fibers are classified according to the part of the plant from which they are extracted: Bast or stem fibers from jute, bananas, flax and hemp plants; Leaf fibers from sisal, pineapple and screw pine; Fruit and seed fibers from coir, oil palm and cotton as shown in Figure 2.3. Fibers originating from the bast stem, leaf and fruit are naturally organized into bundles and are therefore called fiber bundles (Vincent, 2000). In general, the leaf fibers are coarser than the bast fibers (Brouwer, 2000)

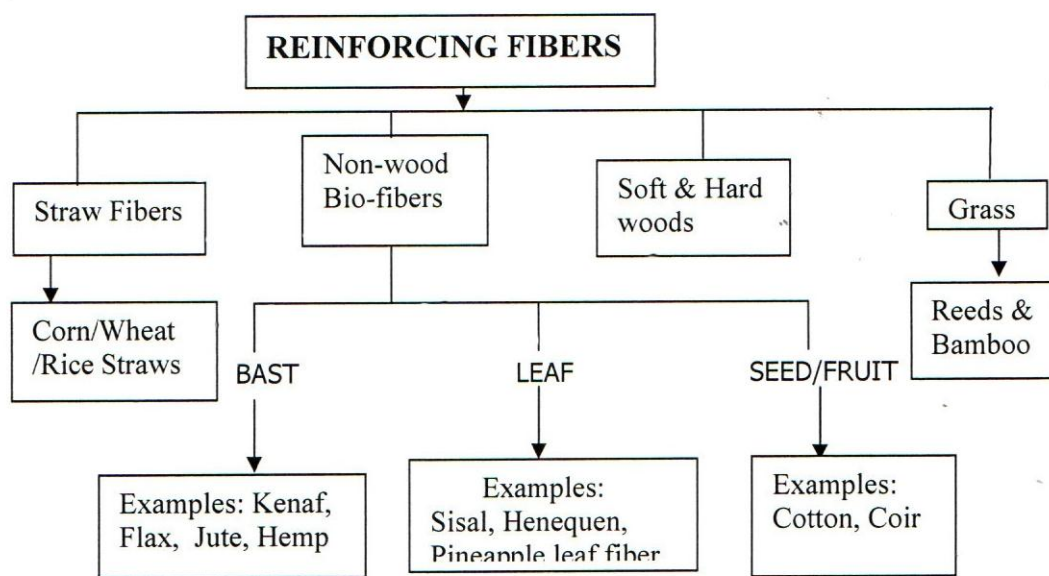


Figure 2.3 Classification of plant fibers, which can be used as reinforcement or fillers in polymers

Source: Mohanty *et al*, 2002

Traditionally, bast and leaf (the hard fibers) types especially sisal, pineapple, jute and kenaf have been used for products, such as ropes, twine, and burlap. But natural fibers have become more prevalent in fashion over the last decade. Bast natural fibers used for apparel applications include ramie and milkweed fibers. They provide new aesthetic and physical properties such as high moisture regain, rendering the fabric being more comfortable. Recently, jute and pineapple fibers have also been blended with polyester or cotton and made into coarse fabrics.

In the recent past, bast and leaf fibers have been increasingly used in composite applications. These are flax, hemp, jute, kenaf, banana and sisal (Williams and Wool,

2000). Due to sisal's low density combined with relatively stiff and strong behaviour, the specific properties of sisal and pineapple fibers can compare well with those of glass and other conventional fibers as reflected in Table 2.1.

2.4.2 Sisal fibers

Sisal belonging to the family *Agave sisalana* is a perennial hardy plant, which unlike the other plants is not a seasonal crop. Sisal, though native to tropical and sub-tropical North and South America, Mexico and the Caribbean, is widely grown in tropical countries of Africa, the West Indies and the Far East (Bismark *et al*, 2001)

Sisal, shown in Figure 2.4(a) is a reasonably drought tolerant crop and can be grown in areas with as low rainfall as 600mm per annum though performs better at about 1200mm of rainfall reasonably distributed throughout the year (Export processing zone-Kenya, 2005).



Figure 2.4 (a) Sisal field with mature sisal plants taken at Athenai sisal estate.

It can survive in almost all soil types and its input costs are least for its survival, regeneration and maintenance on sustainable basis. The sisal plant has a stalk on which the succulent leaves are arranged spirally. Its dimensions are about 1 to 2 m in height, with a diameter of about 20 cm. The lance-shaped leaves, between 200-300 leaves, growing out from the stalk in a dense rosette, are fleshy and rigid, with dark green colour. Each is 0.8m to 1.5 m long, 7cm to 8 cm wide at the base, and 10 to 15 cm across at the widest portion terminating in a sharp spine and yields parallel hard fibers. The plant matures fully in 4 to 8 years after planting.

Sisal fiber shown in Figure 2.4 (b) is extracted from the leaves of the sisal plant. It is grouped under the broad heading of the "hard fibers" among which it is placed second to

manila in durability and strength (Joseph *et al*, 1999). Nearly 4.5 million tonnes of sisal fibers are produced every year throughout the world with China and Brazil being the main producing countries.



2.4 (b) Sisal fibers on the drying line at Mogotio sisal factory

Kenya is the third largest producer of sisal fiber (Economic Review of Agriculture, 2006) producing the world's best quality sisal fiber that is used mainly in the manufacture of high quality and premium products including high quality carpets, specialty paper, gypsum blocks and composites. Kenya's production increased to 25,000 metric tonnes in 2003 (Sisal Board of Kenya, 2004).

Though sisal fiber is the most widely used natural fiber, and accounts for half the total production of natural fibers, a large quantity of this economic and renewable resource is still under-utilized (Bismark *et al*, 2001). It is mainly used as ropes in marine industry and agriculture. Other applications of these fibers include twines, cords, upholstery, padding and mat making, fishing nets, fancy articles such as purses, wall hangings and table mats. They have also been used to manufacture strong, cheap, fire resistant corrugated roofing panels. Natural fiber composites are well suited for use in the worldwide automotive industry, which has come under strong pressure to produce environmentally friendly cars. In 1999, natural fibers used in the automotive industries comprised 75% flax, 10% jute, 8% hemp, 5% kenaf and 2.5% sisal (Khoathane, 2005).

The use of long vegetable fibers may provide other benefits. For example, it has been reported that replacement of wood fiber by flax/sisal in interior door panels of Mercedes-

Benz E-class car resulted in a weight reduction of 20% and a strength increase for those components (<http://www.bc.bangor.ac.uk/suscomp/index.htm>, 2005). Past studies comparing the mechanical properties of glass fiber with that of natural fibers (flax, hemp and jute) as reinforcement in both thermoset and thermoplastic matrices indicated that the potential of natural fibers is far from being realized as observed in Figures 2.5, 2.6 and 2.7. These figures showed that whilst the stiffness and to a lesser extent the strength (on a volume to volume basis) of hemp reinforced polyester is at par with that of glass fiber reinforced material, toughness is substantially inferior. The results also indicated that for equivalent fiber volume fractions, plant reinforced laminates exhibit works of fracture in an order of magnitude lower than those of glass fiber reinforced materials with toughness being a major area of concern. A significant contribution to the high work of fracture exhibited by glass fiber reinforced composites was attributed to fiber pull out.

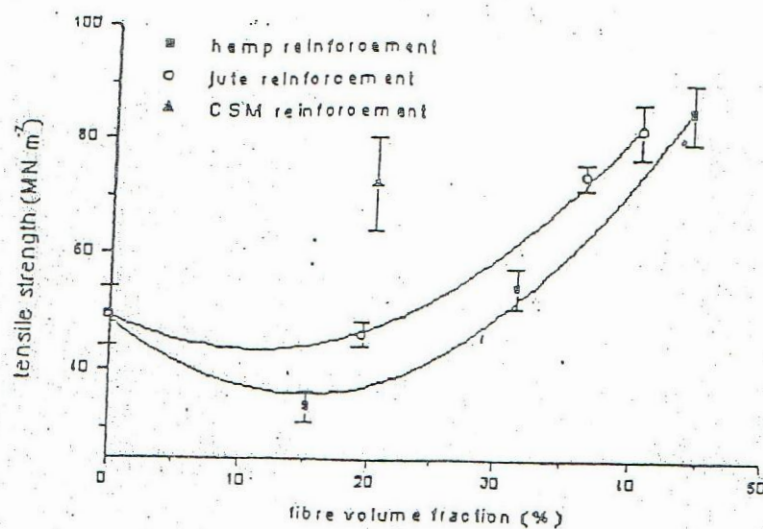


Figure 2.5 Variations of tensile strength with fiber volume fraction (non - woven hemp, jute and chopped strand mat glass reinforced polyester laminates)

Source:<http://www.bc.bangor.ac.uk/suscomp/index.htm> (2003)

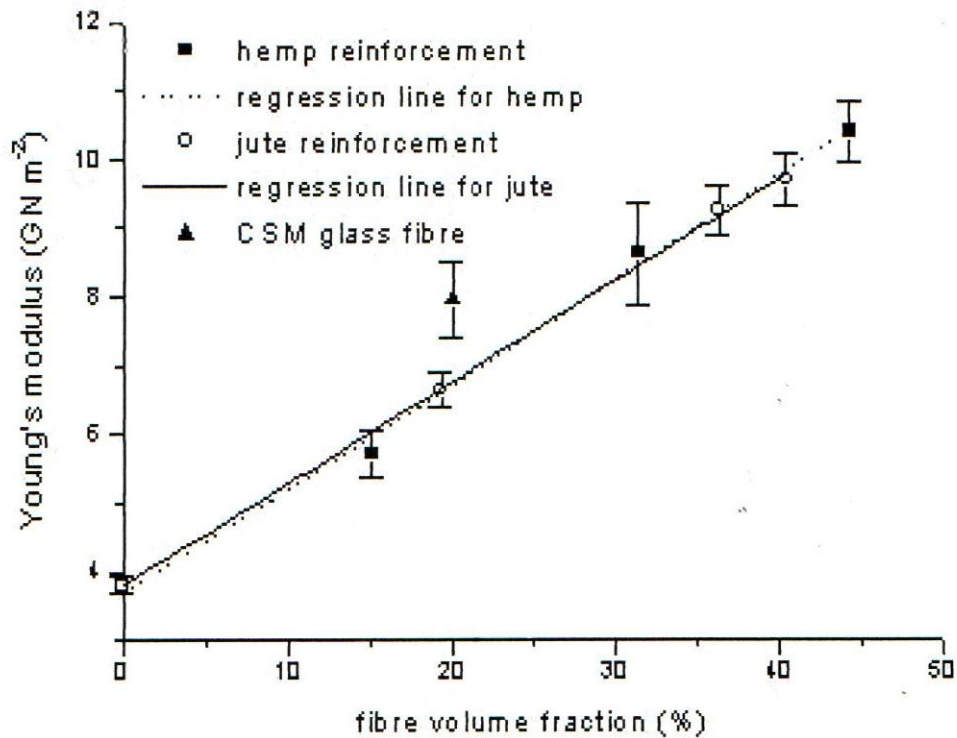


Figure 2.6 Variation of Young's modulus with fiber volume fraction (non - woven hemp, jute and chopped strand mat glass fiber reinforced polyester laminates)

Source : <http://www.bc.bangor.ac.uk/suscomp/inder.htm> (2003)

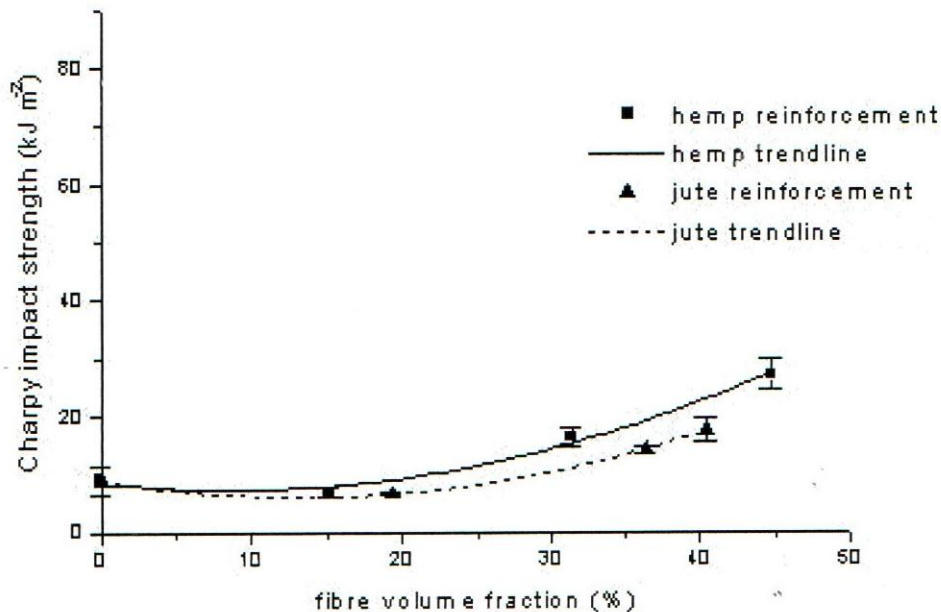


Figure 2.7 Variation of charpy impact strength (unnotched) with fiber volume fraction (non-Woven hemp, jute and chopped strand mat glass fiber reinforced polyester laminates)

Source : <http://www.bc.bangor.ac.uk/suscomp/inder.htm> (2003)

2.4.3 Pineapple Leaf Fiber

Pineapple leaf fiber (Palf) is obtained from the leaves of the pineapple plant (*Anannus comosus*) shown in Figure 2.7 belongs to the Bromeliaceae family. Pineapple is the second harvested fruit of importance after bananas, contributing to over 20 % of the world production of tropical fruits. According to FAO projections, the world market for fresh pineapple is expected to expand over the next decade (Asopa, 2003). These fruits grow and yield best in areas with warm and relatively uniform climate all year round (Economic Research Service-USDA, 2003). They are largely grown in tropical America, in the Far-East Asia countries and Africa (Mwaikambo, 2006). Kenya is ranked ninth in total production with an average of 600000 tonnes in 2004 (Marketing News; 2005). It is in the Philippines, Taiwan and India where the pineapple plant is used as a source of fiber (Mwaikambo, 2006).



Figure 2.8 Pineapple plants in a farm in Litein Division of Kericho District.

Recently, pineapple fibers have also been blended with polyester or cotton and made into coarse fabrics (Zhang, 2003). The pineapple plant has a very short stem which first produces a rosette of dark green sword shaped leaves of about 915mm long and 50-76mm wide. These leaves yield strong white fine silky fiber of fine quality and its structure is without mesh. The pineapple fiber bundles are separated from the pineapple leaf by hand and sometimes by machines. The hand separation (a laborious and costly process) involves the stripping off of the fiber from retted leaf.

The hand lay-up method yields 2%-3% dry fiber from about one tonne of pineapple leaf, which is 20-27 kilogram of dry fiber. The machine separation though facilitating production process is slower than the hand method (Mwaikambo, 2006). Since the pineapple plant is a special crop, only limited quantity of fiber is available, therefore no attempt has been made to grade these fibers but in the near future a considerable increase in the production is envisaged (Mishra *et al*, 2004).

The superior mechanical properties shown in Table 2.2, of pineapple leaf fiber are associated with its high cellulose content and comparatively low microfibrillar angle. Studies of stress-strain relationship have indicated the fiber to be sufficiently strong and highly resistant to abrasive wear with the fiber having an initial modulus of 34.5-82.51 GN.m⁻², a tensile strength of 413- 1627 MN.m⁻² and an elongation of 0.8-1.6 %

Table 2.2 Chemical composition and structural parameters of natural fibers

Fiber	Cellulose (%)	Hemi-cellulose (%)	Lignin (%)	Extrac-tivies (%)	Ash (%)	Pectin (%)	Wax (%)	Microfibril/ spirral angle (°)	Moisure content (%w.b.)
BAST									
Jute	61-71.5	13.6-20.4	12-13	-	-	0.2	0.5	8.0	12.6
Flax	71-78.5	18.6-20.6	2.2	2.3	1.5	2.2	1.7	10.0	10.0
Hemp	70.2-74.4	17.9-22.4	3.7-5.7	3.6	2.6	0.9	0.8	6.2	10.8
Ramie	68.6-76.2	13.1-16.7	0.6-0.7	-	-	1.9	0.3	7.5	8.0
Kenaf	31-39	15-19	21.5	3.2	4.7	-	-	-	-
LEAF									
Sisal	67-78	10-14.2	8-11	-	-	10.0	2.0	20.0	11.0
Palf	70-82	-	5-12	-	-	-	-	14.0	11.8
Henequen	77.6	4.0-8.0	13.1	-	-	-	-	-	-
SEED									
Cotton	82.7	5.7	-	-	-	-	0.6	-	-
FRUIT									
Coir	36-43	0.15-0.25	41-45	-	-	3.4	-	41-45	8.0
WOOD									
Soft	40-44	25-29	25-31	5	0.2				
Hard	43-47	25-35	16-24	2-5	0.4				

Source: Mohanty *et al*, 2000

Utilization of by-products from pineapple culture, canning and juice extraction-pineapple pulp has been encouraged for cattle feed (Asopa, 2003). The leaves can be used in three forms: fresh, dried and in silage (Coppens *et al*, 2001), but much of these leaves are going to waste because of lack of knowledge about their other economic uses.

2.5 Structures and properties of plant fibers

The structure of plant fibers consists of a strong crystalline phase of cellulose and a tough amorphous phase constituting the matrix. Figure 2.9 shows the schematic structure of a plant fiber. The fibers contain continuous cylindrical cells identified as the primary wall P, the outer secondary wall S₁, the middle secondary wall S₂ and the tertiary wall S₃ (Ogola, 2000). The micro fibrils of the S₂ layer trace a helix around the cell wall at an angle θ , which is constant within the particular cell. This angle is called the microfibrilar

spiral angle and is an important factor in determining the mechanical properties of a plant fiber (McLaughlin and Tait, 1980)

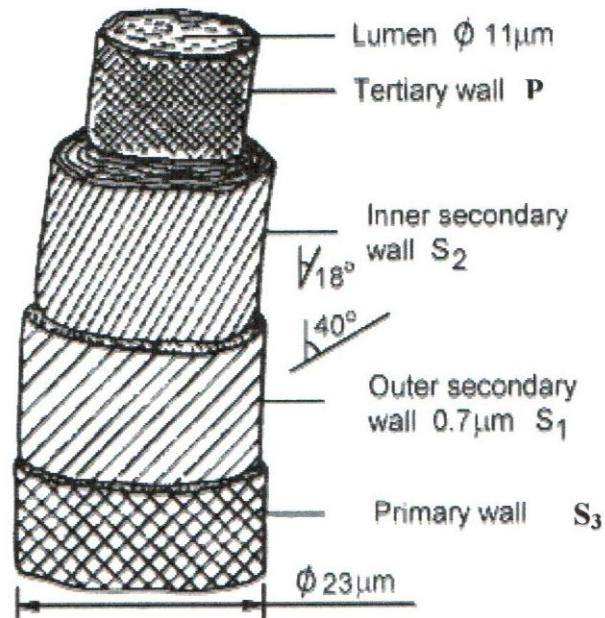


Figure 2.9 Simplified structure of the cell wall showing orientation of the microfibrils in each of the major layers.

Source: Ogola (2000)

2.5.1 Physical properties of plant fibers

Vegetable fibers have density of about half that of glass fibers. These fibers can withstand processing temperatures of up to 250°C (Sreekala *et al*, 2000). The physical structure of the fiber is of several fibrils running along the length of the fiber exhibiting considerable variation in diameter along the length of individual filaments. Jähn *et al* (2002) reported that plant fiber properties directly influence the physical parameters of the fiber-reinforced composites. Quality and other properties of fibers depend on size, maturity and processing methods adopted for the extraction of the fiber (Mohanty *et al*, 2002).

2.5.2 Mechanical properties of plant fibers

The mechanical properties of natural fibers vary considerably depending on the chemical and structural composition, fiber type and growth conditions. Mechanical

properties of plant fibers are much lower when compared to those of the most widely used competing reinforcing glass fibers (Amar *et al*, 2005).

2.5.3 Chemical properties of plant fibers

Fibers from different plant species can appear quite different. However the chemical composition is fairly similar. Plant fibers consist mainly of cellulose, hemicellulose and lignin in different proportions. The polymers' lignin and hemicellulose are responsible for most of the physical and chemical properties such as biodegradability, flammability, affinity towards moisture and degradability by UV light (Satlow *et al*, 1994). The mechanical performance of fibers is dependent upon its chemical composition, chemical structure and cellular arrangement. The properties of the composites depend on those of the individual components and on their interfacial compatibility.

Cellulose forms the main structural constituent of plant fibers and contributes immensely to the mechanical properties of plant fibers. Cellulose is a natural polymer with high strength and stiffness per weight, and it is the building material of long fibrous cells. Selective removal of non-cellulosic compounds constitutes the main objective of fiber. The chemical composition and structural parameters of sisal fiber and Palf in comparison with other plant fibers are presented in Table 2.2.

The chemical structure of cellulose is presented in figure 2.10

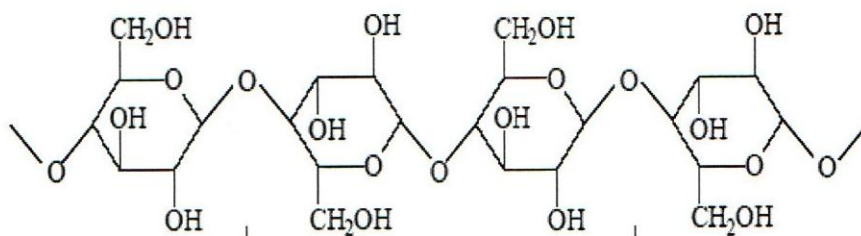


Figure 2.10 Chemical structure of cellulose

2.6 Moisture absorption

Natural fibers are hygroscopic in nature and they absorb or release moisture depending on environmental conditions. A major limitation, therefore of using natural fibers in durable composite applications is their high moisture absorption resulting in dimensional instability due to swelling (Panigrahi *et al*, 2002). Swelling of fibers can lead to micro-cracking of the composite and degradation of mechanical properties. Strong intermolecular fiber-matrix bonding decreases the rate of moisture absorption in biocomposite. To increase the interface adhesion between the fiber and matrix, the fiber surface must be cleaned and chemically modified and the surface roughness increased (Yuan *et al*, 2002). This can be achieved by treating these fibers with suitable chemicals to decrease the hydroxyl group in the fibers. Stamboulis *et al*, (2000) reported that the moisture absorption and swelling of the treated flax fiber composites is approximately 30% lower than that of composites based on untreated flax fibers. Water absorption is generally considered to be disadvantageous, especially in composites. Migration of water through the polymer can lead to a disturbance of the fiber-matrix interface, reducing the overall strength and resulting in the dimensional instability of composites. New applications and end uses of natural fiber composites for decking, flooring, and outdoor facilities, for example, and their exposure to atmosphere or contact with aqueous media, have made it necessary to evaluate the water uptake characteristics of natural fiber thermoplastic composites. Because of the hygroscopic nature of natural fibers, water uptake of composites containing these fibers as fillers and/or reinforcement influence the performance and mechanical properties, Rai and Priya (2006) and can be a limiting parameter as far as the final application of the composite is concerned.

2.7 Chemical Treatment of natural fibers

Natural fibers are amenable to modification as they bear hydroxyl groups from cellulose and lignin. The hydroxyl groups may be involved in the hydrogen bonding within the cellulose molecules thereby reducing the activity towards the matrix. Chemical modifications may activate these groups or can introduce new ways that can effectively interlock with the matrix.

2.7.1 Surface chemical modifications of natural fibers

Several studies have shown the influence of various types of chemical modification on the performance of natural fiber and fiber-reinforced composites. Natural fibers are generally treated with coupling or chemical agents such as silane, isocyanate, alkali and peroxide to improve the adhesion between the hydrophobic matrix and natural fibers. Fiber modification with the various coupling agents has achieved various levels of success in improving fiber strength, fiber fitness and fiber-matrix adhesion in natural fiber composites.

2.7.2 Mercerization (alkali treatment)

Alkali treatment of cellulosic fibers, also called mercerization, is the usual method to produce high quality fibers (Ray *et al.*, 2001). Alkali treatment improves the fiber-matrix adhesion due to the removal of natural and artificial impurities (Mishra *et al.*, 2001). Moreover, alkali treatment leads to fibrillation which causes the breaking down of the composite fiber bundle into smaller fibers meaning that alkali treatment reduces fiber diameter and thereby increases the aspect ratio. Therefore, the development of a rough surface topography and enhancement in aspect ratio offer better fiber-matrix interface adhesion and an increase in mechanical properties (Joseph *et al.*, 2000). Alkali treatment increases surface roughness resulting in better mechanical interlocking and the amount of cellulose exposed on the fiber surface. This increases the number of possible reaction sites and allows for better fiber wetting.

The following reaction takes place as a result of alkali treatment:



Several other studies (Mishra *et al.*, 2002; Joseph *et al.*, 2000; Sreekala *et al.*, 2000) on alkali treatment reported that mercerization led to the increase in the amount of amorphous cellulose at the expense of crystalline cellulose and the removal of hydrogen bonding in the network structure.

2.7.3 Acetylation

Acetylation of natural fibers is a well-known esterification method to introduce plasticization to cellulosic fibers. Acetylation has been extensively applied to wood

cellulose to stabilize the cell wall, improving dimensional stability and environmental degradation. One of the modification techniques employed by the Okura Company in Japan was to produce esterified woods (Mohanty *et al.*, 2001), which would be molded into plastic sheets by hot pressing.

2.8 Plastic Resins

Plastics are organic high polymers that are formed in a plastic state either during or after their transition from a small-molecule chemical to a solid material. Plastic resin is any of a large class of synthetic products usually of high molecular weight having some physical properties of natural resins while being very different chemically (Encarta Encyclopedia, 2004: plastics). The commonly found resin (matrix) is polymeric (plastic) and to a lesser extent ceramics and metal. According to Strong (1996), polymeric composite materials represent about 90% of all composites. The resin's main function is to hold all reinforcements together, thus allowing the applied force to be transmitted to the reinforcement. Other functions of the resin include protection and prevention of the composite fiber from damage such as crack propagation with the material. All polymers (plastics) can be divided into two groups, thermosets and thermoplastics (Shaharuddin *et al.*, 2005).

2.8.1 Thermosets

Thermoset resins react during processing to form cross-linked structures that cannot be remelted or reprocessed and provide sufficient mechanical properties. Thermosets are stiff and do not stretch the way that elastomers and thermoplastics do. The polymer viscosity is low in thermosets (0.1-10 Parts; Lystrup, 1997) compared with thermoplastics (100-1000 Parts; Brüning and Disselbeck, 1992). Thermosetting resins such as epoxy, unsaturated polyester (as in fiberglass), and phenolic are commonly used today in natural fiber composites and in composites requiring higher performance applications (Maschinenwesen, 2006). They may be supplied in liquid form or as a partially polymerized solid molding powder in their uncured condition.

2.8.2 Polyester resin

Unsaturated polyester (UP) are extremely versatile in properties and applications and are a popular thermoset used as the polymer matrix in composites (Sharifah *et al*, 2005). They are widely produced industrially as they possess many advantages compared to other thermosetting resins including room temperature cure capability, good mechanical properties, in particular stiffness and strength at acceptably low price levels and transparency (Kim *et al*, 1994). They can be formed to the finished product shape with or without pressure and polymerized by using chemicals or heat (Encarta Encyclopedia, 2004: plastics). Polyester resin is a thermosetting resin made from an UP such as one formed from glycol and malic acid or fumaric acid. It is the most widely used resin in making casts and molded products (Encarta Encyclopedia, 2004: plastics).

2.8.3 Epoxy resins

Epoxy resins are thermosetting resins in which the uncured epoxy is reacted with a curing agent or hardener. Epoxies are used by the plastics industry in many ways, one of which in combination with glass fiber. Liquid epoxy resins are impregnated into the fibers to produce high-strength composites providing electrical and chemical properties and heat resistance. Epoxy resins are good for producing composites with superior mechanical properties with the major drawback in industrial use being their brittleness and high cost. Typical uses of epoxy- glass reinforced plastics are in aircraft components, pipes, tanks, tooling jigs and fixtures. Major outlets for epoxies also include adhesives, protective coatings in appliances and industrial equipment (Nick and Callum, 2004).

2.8.4 Phenolic resins

Phenolic resins, first commercially available in 1910, were some of the first polymers made. Today phenolics are some of the most widely produced thermosetting plastics (Encarta Encyclopedia, 2004: plastics). As molding powders, these resins can be found in electrical uses, as automotive distributor caps, fuse blocks and connectors and appliance handle knobs and base. Phenolic is the most popular binder for holding the various plies of wood together in plywood (Encarta Encyclopedia, 2004: plastics). In general, phenolics have high rigidity, dimensional stability and exceptional heat and fire

resistance due to the highly cross linked aromatic structure. The high brittleness and cure shrinkage are the major drawbacks (Paiva *et al*, 2000).

2.8.5 Thermoplastics

Thermoplastic resins consist of long molecules each of which may have side chains or groups that are not attached to other molecules. They can be repeatedly melted and solidified by heating and cooling so that any scrap generated in processing can be reused (Hull and Clyne, 1996).

2.9 Fillers

In order to impart certain specific properties, polymers are usually compounded with additives, which modify and improve desired characteristics of the polymers such as stiffness, strength, color, weatherability, flammability and resistance for electrical applications and ease of subsequent processing. Because of their low cost, fillers are important in reducing the overall cost of polymers. Fillers are also known to improve dimensional stability, lower shrinkage and post mould distortion, fire resistance due to decreased heat of combustion and increase production cycle time (Waterman and Ashby, 1991). In reinforced plastics, fillers' effectiveness depends on the nature of the bond between the filler material and the polymer chains (Kalpakjian, 1995). Some of the common fillers for plastics are starch, chalk, carbon, metallic oxides, powdered polymers, chopped cloth and magnesium carbonate (Waterman and Ashby, 1991). Cellulosic fillers of a fibrous nature have generated great interest because they can give composites improved mechanical properties compared to those containing non-fibrous fillers materials (Joseph *et al*, 2000).

2.10 Development of Natural Fiber Composites

Since 1941, the study on fiber-reinforced plastic composites has gained increasing attention of researchers and manufacturers (Joseph *et al*, 2000). Natural fibers have for long served many useful purposes but the application of material technology for the utilization of these fibers as reinforcement in polymer matrix has taken place in recent years. The increased interest in natural fiber-reinforced composites is due to the high performance in mechanical properties, significant processing advantages, excellent

chemical resistance, low cost and low density (Mwaikambo, 2006). The uses of these natural annually renewable resources provide positive environmental benefits with respect to ultimate disposability and raw material utilization. Recent studies indicate that plant-based natural fibers can be used as reinforcement in polymer composites, replacing the expensive and non-renewable synthetic fibers such as glass, because of their potential for recyclability (Mohanty *et al*, 2001). These fibers, with their moderately high specific strength and stiffness have the potential for making low cost composites.

2.11.1 Fabrication techniques

During the fabrication processes, it is the matrix, the important partner, which must soften and flow before it hardens. Figure 2.11 shows the essential differences in the stress/strain properties of the phases. The fiber should be stiff and strong. The matrix which is less stiff has a larger extension at break so that the fiber reaches its full extension and realizes its full strength before the matrix falls. Some major methods of molding are contact molding, pultrusion, rotational molding, compression molding, injection molding and extrusion.

2.11.2 Contact molding

Contact molding is defined as a low pressure molding method in which only one side is the mold surface. There are two principal techniques namely hand layup and sprayup. In the hand layup process, the reinforcement is manually fitted to a mold wetted with catalyzed resin mix, roller pressed to expel air after which it is saturated with more resin with a brush as the rolling continues. Contact molding is used in making products with high surface area to thickness ratios such as swimming pools, boat tubs, shower units and housing (Hughes *et al*, 2002). It is an inexpensive process as it makes use of simple tools. The strength of any part is in the fibers and not in the resin. Spray layup, or "sprayup," differs from hand layup in that it uses mechanical spraying and chopping equipment for depositing the resin and reinforcement. Although spraying can be automated, these processes are relatively slow and labour costs are high. (Beall, 1998).

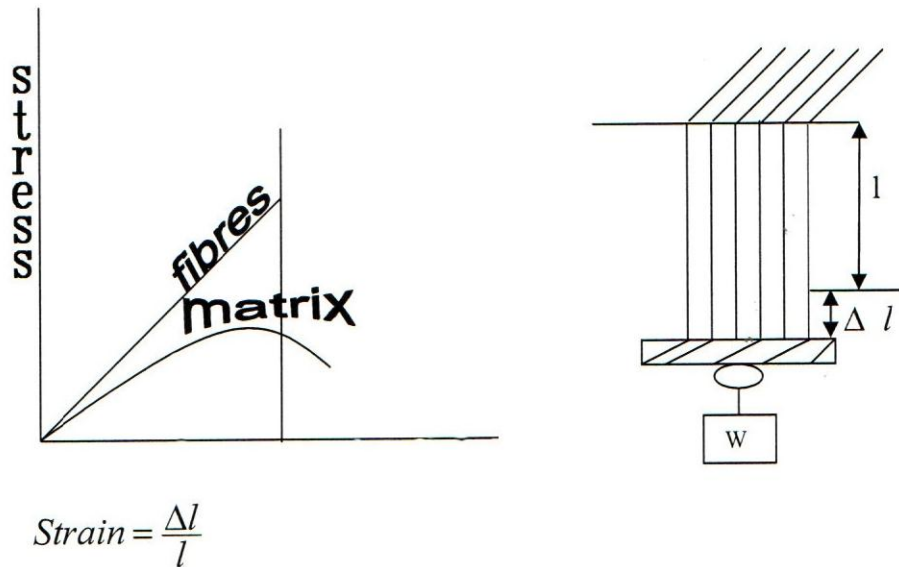


Figure 2.11 Stress/strain curves for fibrous reinforcement and matrix

Desirably, the energy stored at failure (area under stain/stress curve) is as large as possible since this indicates a tough composite (Hull and Clyne, 1996)

2.11.3 Pultrusion

The pultrusion process makes long shapes with various constant profiles such as rods and tubing. In this process, the continuous reinforcement is pulled through a thermosetting polymer bath and then through a long heated steel die. The product is curved during its travel through the die and cut into desired lengths. The most common material used in pultrusion is polyester with glass reinforcement (Depro *et al.*, 2002).

2.11.4 Rotational molding

Rotational molding is a process for manufacturing hollow plastic products which involves power mixing, melting, sintering and melt solidification. Various aspects of the rotational molding process have been studied by several researchers (Throne, 1979;

Crawford, 1992). Fundamental research on rotational molding has been directed to reduce the molding cycle time and to optimize the mechanical properties of final parts.

2.11.5 Filament Winding

This is a technique that is most easily described as loom combined with a CNC machine. Single or multiple tows (yarns) are wound around a mandrel. This type of manufacturing is expensive but offers a product that may be highly engineered and therefore stronger than typical fabrication techniques using prepregs or wet lay up with vacuum bagging (Depro *et al*, 2002).

2.12 Determination of mechanical properties

The mechanical properties of a natural fiber-reinforced composite depend on many parameters, such as fiber strength, length and orientation, in addition to the fiber-matrix interfacial bond strength (Wang, 2004). A strong fiber-matrix interface bond is critical for high mechanical properties of composites. A good interfacial bond is required for effective stress transfer from the matrix to the fiber whereby maximum utilization of the fiber strength in the composite is desired (Karnani *et al*, 1997). In addition, factors like processing conditions/techniques have significant influence on the mechanical properties of fiber reinforced composites (George *et al*, 2001). The bend test is a simple and inexpensive qualitative test that can be used to evaluate both the ductility and soundness of a material. It is often used as a quality control test having the advantage of simplicity of both the test piece and equipment. The three point bending test is widely used to characterize mechanical behavior of materials. The main advantage of a three point bend test is the ease of the specimen preparation and testing.

2.13 Catalysts

A catalyst is a substance that accelerates the rate of a chemical reaction at the same temperature but without itself being transformed or consumed by the reaction. A catalyst participates in the reaction but is neither a chemical reactant nor a chemical product. Catalysts enable reactions to occur much faster or at lower temperatures because of changes that they induce in the reactants (Encarta Encyclopedia, 2004).

From the literature review it is observed that natural fiber composites present immense opportunities to play a role as alternate substitutes for conventional engineering materials. They have special relevance to developing countries like Kenya in view of their low cost and saving in energy. One of the major difficulties of natural fibers is that their properties are intrinsically dependent on where they are grown, the part of the plant they are harvested from, the maturity of the plant and how the fibers are harvested and preconditioned. These factors result in significant variation in properties compared to their synthetic fiber counterparts (glass, aramid and carbon). Mishra *et al*, (2004) in their review on pineapple leaf fibers, sisal fibers and their bio-composites suggested additional research on the physical-mechanical properties of these natural fibers in order to develop and promote them. Mathur (2006) in his study on composite materials from local resources suggested thorough researches on applications development of natural fiber composites for their durability and cost effectiveness in order to obtain consistent products performance under use conditions. This research shall endeavour to study the mechanical properties of glass/sisal, glass/pineapple, sisal/palf, pineapple and sisal fiber composites in view of achieving a wider acceptance on a large scale.

3.1 Materials

The materials used in this study were sisal, pineapple leave fibers and chopped glass strand mats. The sisal leaves were harvested from Athenai sisal plantation in Mogotio area of Nakuru district and taken to the Athenai sisal factory for the decorticating process. The sisal fibers used for the fabrication of samples were collected from the waste that is washed-off by the water from the fiber decorticating machine at the factory. The pineapple leaves were harvested from pineapple plants in Litein area of Bureti District. The pineapple leaf fibers, shown in figure.3.1 were then extracted by the water retting method. The unsaturated polyester resin and methyl ethyl ketone peroxide (MEKP) catalyst were used in the fabrication of the composite samples.

3.2 Material preparation

3.2.1 Fiber preparation

(a) Sisal fiber preparation

The sisal fibers, washed off from the decorticating machine were collected from within the factory fields. The fibers were thoroughly brushed to remove any remaining cortex and dirt. The brushed fibers were then cut to about 6cm in length, weighed to the required percentage fiber content, wrapped in foil paper and marked ready for further cleaning and drying.

(b) Pineapple fiber Preparation

The pineapple fibers extracted from the leaves by water retting were of sizes ranging from 4-15cm. These fibers were then cut to 4cm in length and weighed to the required fiber content. These fibers were wrapped in foil paper and marked ready for further cleaning and drying.

The fibers were cleaned in commercial detergent solution followed by distilled water and then dried in an oven at 100°C for 24 hours. This removed most of the impurities from the fibers. The cleaned fibers were then ready for the surface modification process. Fibers used without further cleaning were referred to as unmodified.

In this research, alkaline group of sodium hydroxide (NaOH) and a solution of benzene and ethanol at a ratio of 1:1 were used to surface modify the fibers. Surface modification of the natural fibers improves the adhesion between the hydrophilic fibers and the hydrophobic resin. The fibers were soaked in a 5% NaOH solution for 24 hours at room temperature.



Figure 3.1 Long Palf extracted from pineapple leaves

The fibers were then dipped into alcohol to remove excess chemical solution followed by a thorough wash in distilled water and then oven-dried at 100°C for one hour. The dried fibers were chopped to length size of 2-4 mm as shown in Figure 3.2. The fibers were chopped to match the glass fiber chopped strand mats which were used in this study. The chopped fibers were then ready to serve as treated reinforcing agents in the matrix.



Figure 3.2 Chopped Palf

3.3 Composite Fabrication

Randomly oriented chopped pineapple and sisal fibers of 5, 10, 20, 30 and 40 per cent weights were incorporated into the polyester resin in the preparation of the composite samples. A combination of the hand lay-up and compression methods was adopted for the composite fabrication. The hand lay up method is an inexpensive process and makes use of simple tools. The compression process ensures the even spread of the resin and enhances the bonding between the fibers and the resin. Samples of size 150mm x 15mm and varying thickness were prepared using a closed mold. The mold shown in figure 3.3 was thoroughly washed with ordinary detergent, dried and polished with mirror wax.



Figure 3.3 The mold fixture

The releasing agent was then applied on the mold surface followed by the gel coat. The gel coat gives the laminate a shiny smooth finish. The pre-accelerated general-purpose polyester resin was thoroughly mixed with 2% volume MEKP catalyst and applied on the mold. The fibers were then hand-laid on the mold and completely saturated with the resin and then closed, pressed and left to cure at room temperature. Figure 3.4 shows the sample being processed.

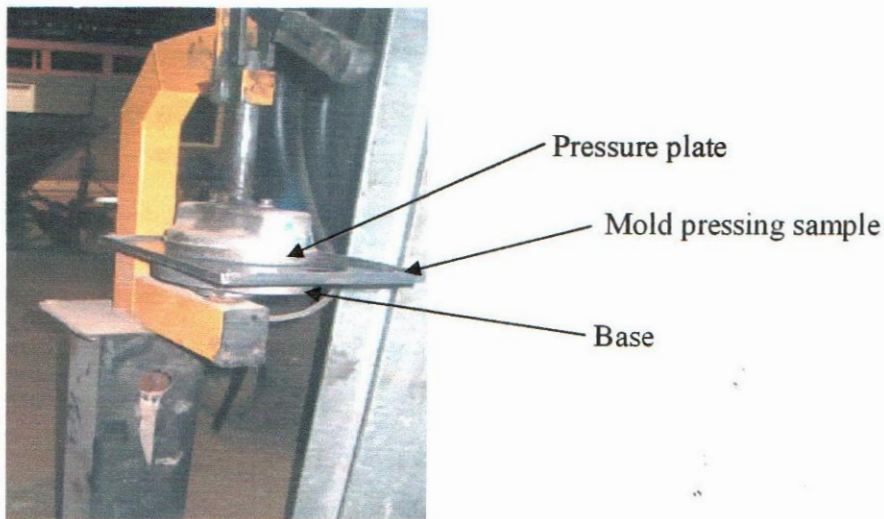


Figure 3.4 Sample being pressed

Sheets were prepared with fibers of (5, 10, 20, 30 and 40%), varying per cent weights. Test samples were then cut from the cured sheets. Figure 3.5 shows a cured sample.

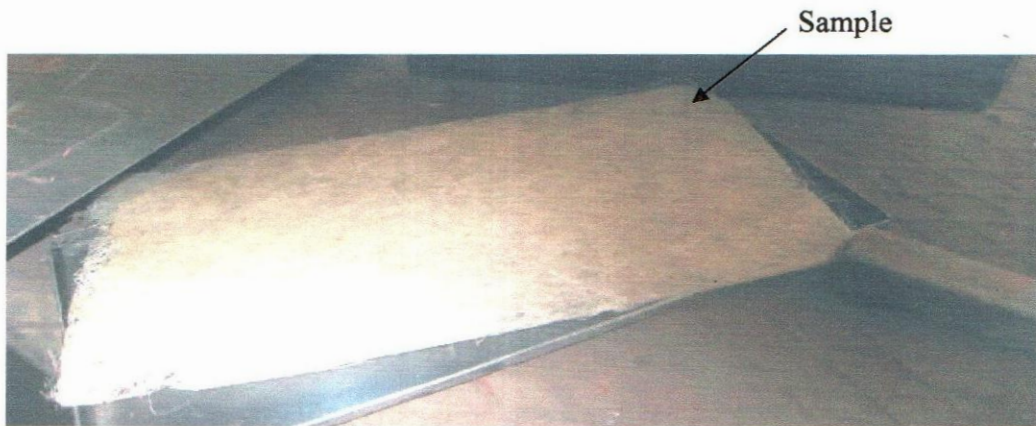


Figure 3.5 Prepared composite sample

3.3.1 Test sample preparation

Test pieces of sizes as per the ASTM standards were sawed off from the prepared samples. They were smoothened at the edges prior to subjecting them to the various tests that were undertaken. Five readings were taken for each test.

3.4 Determination of the mechanical properties

Two mechanical properties-the three-point bend test and hardness test were performed at room temperature of $23^{\circ}\text{C} \pm 2^{\circ}\text{C}$.

3.4.1 Determination of the bending strength

The test samples were prepared according to ASTM standard D790. Samples of $127\text{mm} \times 12.7\text{mm} \times$ the thickness of the laminate were prepared for the test. Each sample was simply supported on roller edges for the three point bend test with a central load applied from the hydraulic Universal Material Tester, 50 kN (WP 310). The test span was set to 100mm. The experimental set up was as shown in figure 3.6.

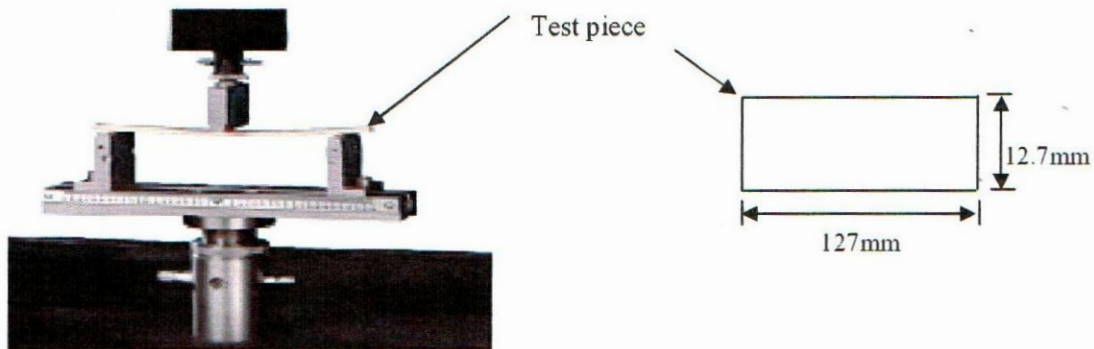


Figure 3.6 Three point bend test set up

The load applied at specified cross-head rate was fixed for a value within the $\pm 10\%$ of the calculated R using equation 3.0.

$$R = \frac{ZL^2}{6d} \quad \text{Equation 3.0}$$

Where:

R = rate of cross head motion in mm/min

Z = rate of straining of the outer fiber in mm/mm/min

L = support span in mm

d = depth of beam in mm

The constant load was then applied on test piece. The testing was terminated when the maximum strain in the outer surface of the specimen had reached the maximum strain of 5 % or rupture occurred. Five consistent test piece results were recorded for each fiber loading composition.

When a homogeneous elastic material is tested in three-point system, the maximum stress occurs at the midpoint. This stress can be evaluated for any point on the load deflection curve using equation 3.1.

$$\sigma_f = \frac{3PL}{2bd^2} \quad \text{Equation 3.1}$$

Where:

σ_f = stress in the outer specimen at midpoint in MPa

P = load at a given point on the load deflection curve in N

L = support span in mm

b = width in mm of beam tested

d = depth in mm of beam tested

The test was done at Eldoret Polytechnic material science laboratory.

3.4.3 Determination of Hardness Value

The resistance to indentation is generally used as a measure of hardness. Hardness readings were performed according to ASTM D2240-97 (ASTM 1998) using the Vickers micro- hardness tester (Shore Instrument and MFG Co., Freeport, NY) shown in figure 3.7. The test piece was set to sit on the machine table. The pressure foot of the instrument was pressed on to the specimen, making sure that it was parallel to the surface of the specimen. The hardness values were read within 15 seconds after the pressure foot was in firm contact with the specimen. Each test piece was subjected to five randomly spread hardness readings and the results averaged.

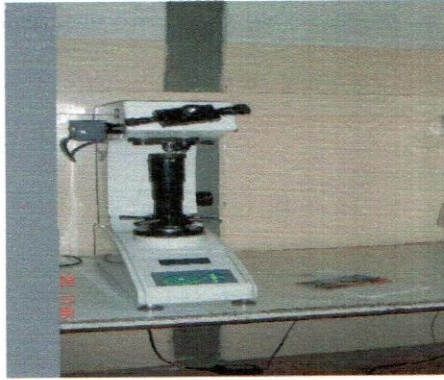


Figure 3.7 Vickers micro-hardness testing machine

3.4.4 Physical Properties

3.4.4.1 Determination of water Absorption

The water absorption samples were prepared in accordance to ASTM D570-99 standards and cut to sizes of 76.1mm x 13.2mm x thickness of test piece. They were put in an oven and dried at $50^{\circ}\text{C} \pm 3^{\circ}\text{C}$ for twenty four hours and weighed immediately upon removal. The samples held horizontally were then soaked in distilled water for twenty four hours. They were removed and the excess water on the surface wiped off using a clean cloth before weighing. The percentage increase in mass was calculated as follows:

$$Q = \frac{W_1 - W_0}{W_0} \times 100 \quad \text{Equation 3.2}$$

Where:

W_0 = Mean mass in grams of the sample before immersion in water for 24 hours at room temperature.

W_1 = Mean mass in grams of the sample after immersion in water for 24 hours at room temperature.

3.4.4.2 Determination of the thickness swelling

The thickness swelling samples were 76mm x 76mm x laminate thickness in size. Their thicknesses were measured midway along each side at room temperature and the results averaged. The samples held horizontally during the test, were then soaked in

results averaged. The samples held horizontally during the test, were then soaked in distilled water for twenty four hours. The excess water was drained upon removal from the water before measuring the new sizes at the same previous points.

λ , the thickness swelling of the samples was calculated according to ASTM standard D1037-03 as follows:

$$\lambda = \frac{T_1 - T_0}{T_0} \times 100 \quad \text{Equation 3.3}$$

Where: T_0 = Mean thickness in mm of the test samples at room temperature before immersion in water.

T_1 = Mean thickness of the test samples for a period of 24 hours after immersion in water in mm.

3.4.5 Statistical analysis

A minimum of five laminates from each fiber laminate system each giving five samples were tested for their physical and mechanical properties. The following equation was used:

$$s = \sqrt{\frac{\sum (X - \bar{X})^2}{n - 1}} \quad \text{Equation 3.4}$$

Where:

s = Sample standard deviation.

X = The value obtained in a test in the series.

n = The number of tests in the series.

$n-1$ = The divisor

$\bar{X}$ = The mean of the observations.

The variance was obtained using the formula:

$$\text{Variance} = s^2$$

The coefficient of variation (CV) was calculated as follows:

$$\text{C.V.} = \frac{s}{\bar{X}} \quad \text{Equation 3.5}$$

The mean, $\bar{X}$, sample standard deviation, s , variance, and the coefficient of variation, C.V. of each laminate system were determined. The F-distribution was used to compare variances. The F-distribution is used to determine whether the differences in sample means are significant. A minimum of five samples from five laminates processed from each fiber system was used.

However, because of the large number of samples tested, only one table has been presented for each test parameter in Appendix A-D.

CHAPTER FOUR

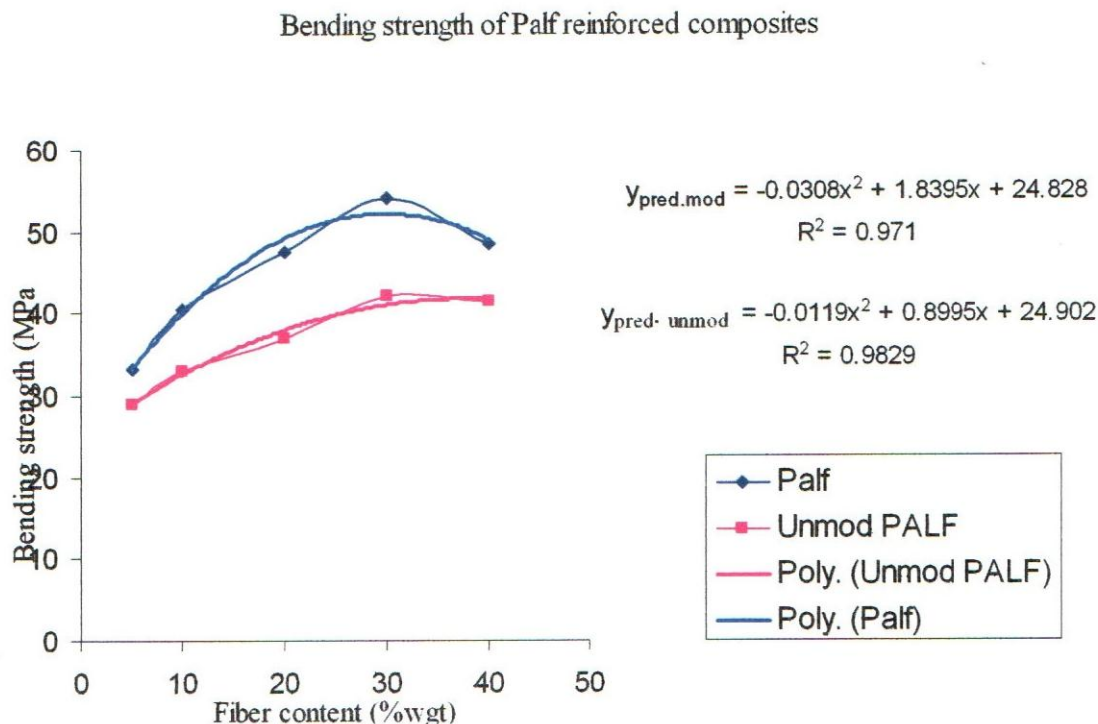
RESULTS AND DISCUSSION

4.1 Mechanical Properties

4.2.1 Bending strength

(a) Palf polyester composites

Bending strength of Palf polyester composites increased with increasing fiber content though a drop in strength was observed at 30 wgt% fiber content as shown in figure 4.1. These findings suggest that the amount of fiber (up to an optimum) in the composite has an influence on strength properties. In their study of Palf polyester composite, Mishra *et al*, (2001) reported that the bending strength increased linearly to 85 Mpa with fiber weight fraction of 30% then a decrease was observed. Uma Devi *et al*, (1997) also reported similar observations. They reported a bending strength of 77.4 Mpa at 30 wgt% fiber for 2%NaOH fiber treatment and a leveling off in strength



Figures 4.1 Bending strength of short modified and unmodified Palf reinforced composites

In this study, an influence of chemical modification on the bending strength of palf composite was observed to enhance the bending strength of the resulting composite. The sodium hydroxide removed the wax, cuticle layer, and part of lignin and hemi cellulose. It also destroyed the hydrogen bonding in cellulose hydroxyl groups of the fibers, which in turn improved the bonding with the polymer matrix. The 1:1 ethanol and benzene solution treatment of 24 hours at room temperature removed waxes, natural oils and other impurities from the fibers. Good fiber – matrix bonding can be established since a major reaction takes place between the hydroxyl groups of cellulose and the chemical used for the surface treatment (Mishra *et al*, 2001; George *et al*, 1998).

The bending strength of unmodified palf composite was observed to increase with fiber content by 44.8% and modified palf increased by 62.4%. These observations agree with Samal *et al* (1994) and Uma Devi *et al* (1997) who concluded in their research findings that chemically modified palf have significantly higher mechanical strengths than that of unmodified palf. Observations of 23.6% and 44.7% increase in NaOH and Cyanoethylate fiber treatments respectively were reported.

98.3% of the variation in strength was accounted for by the variations in the fiber content of the unmodified whereas 97.1% variation was observed in the modified palf as shown in figure 4.1. From Table X in the appendix the F-value with 4 degrees of freedom for both the numerator and denominator at the 5% level of significance is 6.39. With the F-value of 3.1556×10^{-4} the data does not indicate that the relationship between the fiber content and strength in the unmodified palf composite is stronger than the strength realized in the modified palf.

Mokhtar *et al*, (2007) concluded in their study that as the palf loading in polypropylene (PP) increased in terms of weight percent, bending strength in composite gradually increased. The gradual increase trend showed that palf can withstand bending forces to a great extent since their high crystalline fibrils content are strong and can share the load applied in the matrix effectively.

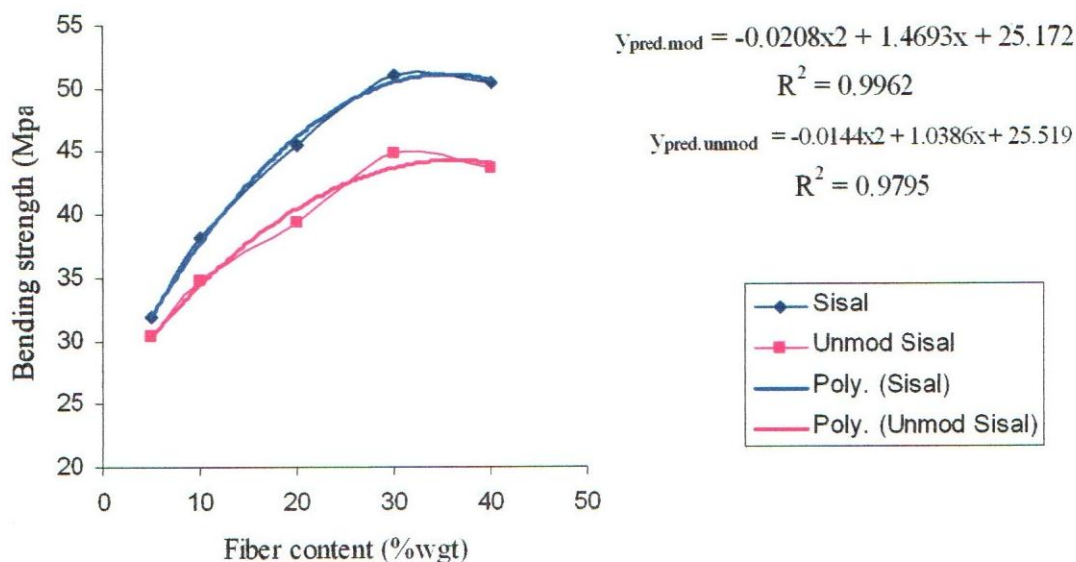
(b) Sisal polyester composites

Surface modified sisal fiber reinforced composites registered an optimum bending strength at 30 percent weight (wgt %) fiber content with a gradual increase in strength

from 33.36 MPa to 54.17 MPa representing 62.4% increase as in figure 4.2. Unmodified sisal recorded 48.1% increase in strength over the same fiber content range with a recorded strength of 24.262 MPa to 40.382 MPa as shown in Figure 4.2. Similar results were observed by Athijayamani *et al*, (2009) who recorded bending strength of 88.9 MPa at 30 %wgt for sisal treated fibers and 72.7 MPa for untreated fiber, an increase of 22.2%.The fibers were alkali treated for four hours.

Poor dispersion due of the unmodified fibers was observed when laying the fibers as they tended to conglomerate. This could be attributed to the fact that natural fibers are hydrophilic. The influence of chemical modification on the bending strength of composites in this study was observed to enhance the bending strength of the resulting composite. Mishra *et al*, (2002) reported in their study that the mechanical properties of surface modified sisal-polyester biocomposites are at an optimum at a fiber loading of 30 wt. % and had a high recorded bending strength of 153.9 MPa in 5% alkali treatment. In this present work, strength of 51.06 MPa was observed.

Bending strength of Sisal fiber reinforced composites



Figures 4.2 Bending Strength of short Sisal fiber reinforced polyester composites

The difference could be attributed to fiber extraction and composite fabrication methods. George *et al*, (2001) pointed out in their study that factors like processing conditions and techniques have significant influence on the mechanical properties of fiber reinforced composites.

(c) Sisal/ Palf polyester composites

The composite sample from sisal/palf hybrid displayed higher strengths at all levels in comparison with either sisal or palf composite samples suggesting that a stronger product may be obtained from combining the two fibers. Figure 4.3.represents the bending strength of hybrid composite sample of sisal and palf.

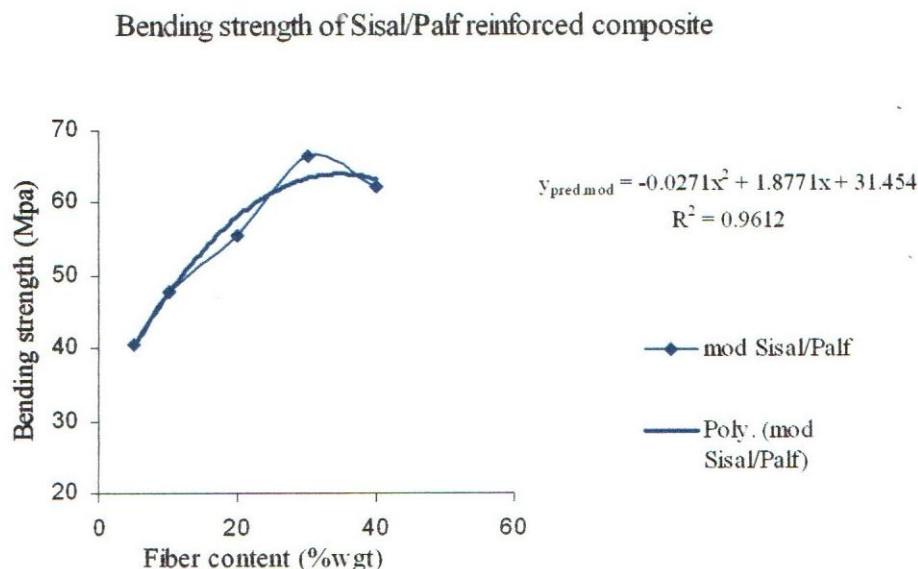


Figure 4.3 Bending Strength of modified Sisal/ Palf polyester composite sample

Observations similar to those obtained in the sisal fiber composite sample were noted with sisal/palf hybrid samples. The unmodified sisal/palf composite sample showed a stronger relationship than the modified sisal/palf composite sample with a recorded 96.12% for unmodified sisal/palf fibers and 92.05% for the modified fibers.

Consequently, the palf can withstand bending forces which comprise both compressive forces and tensile stress. This observation agrees with findings from Jähn *et*

al, (2002) who concluded in their study that palf polyester composites possess superior mechanical properties when compared to other cellulose-based natural fiber composites. Williams and Wool (2000) reported that mechanical properties are determined by the cellulose content and microfibril angle. A high cellulose content and low microfibril angle are desirable properties of a fiber to be used as reinforcement in polymer composites.

Bending strength of Sisal/Palf fiber reinforced composites

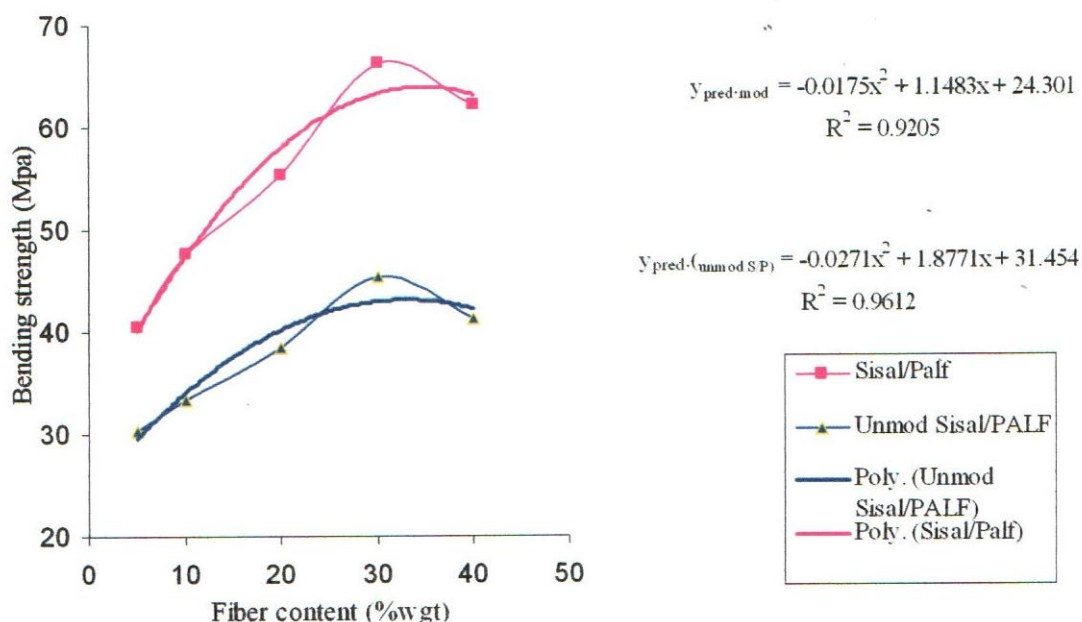


Figure 4.4 Bending Strength of modified and unmodified short Sisal/Palf polyester composite samples.

(c) Hybrid composite of glass and natural fiber

The strengths of glass/sisal and glass/palf composite increased with increasing fiber content up to the 30% wgt content and then a decrease was observed. The incorporation of glass fibers into the composites had a strong effect on product strength. The samples incorporated with glass- glass/sisal and glass/palf fiber composites recorded higher strength values when compared with sisal, palf and sisal/palf reinforcements alone.

Similar findings were observed by Mishra *et al*, (2001) while reporting on the mechanical properties of palf/glass and sisal/glass fiber-reinforced polyester composites. They stated in their findings that tensile, flexural, and impact strengths of palf and sisal-reinforced polyester composites improved with the incorporation of a small amount of glass fibers in the composites thus showing positive hybrid effect. They concluded that optimum glass fiber loadings for palf/glass hybrid polyester and sisal/glass hybrid polyester composites were 8.6 and 5.7 % weight of glass respectively. Rai and Priya (2006) in their study of the mechanical performance of biofiber/glass hybrid composites stated that the addition of a relatively small amount of glass to the biofiber enhanced the mechanical properties of the resulting hybrid composites. The flexural properties of hybrid fiber-reinforced plastics according to Sreekala *et al*, (2002) are not only dependent on the hybrid composition, but also on the arrangement of the material layers.”

Table 4.1 shows the mean strengths of the five fiber compositions tested. These results indicate that composites from palf are stronger in comparison with the sisal composites. The reasons could lie in the chemical properties of the fibers as shown in Table 2.2 in page 19.

Table 4.1 Bending strength in MPa of various modified fiber composites

Fiber content (%wgt)	Sisal	Palf	Sisal/ Palf	Glass/Palf	Glass/ Sisal
5	31.69	33.56	40.582	46.172	43.126
10	37.918	40.826	47.78	54.044	50.434
20	45.272	47.79	55.554	61.064	57.172
30	51.458	54.17	66.4	70.194	69.084
40	47.914	48.456	62.198	67.326	65.936

4.2.2 Hardness values of composites

Figure 4.5 shows the results for hardness tests conducted according to ASTM D2240-97 (ASTM, 1998). According to this standard, the higher the hardness value the harder the material and the lower the depth of penetration. The hardness value of glass/sisal and glass/palf composites are observed to have the same hardness values at 5 and 20 %wgt fiber content. This suggests that the two laminates offer equal resistance to indentation.

fiber content. This suggests that the two laminates offer equal resistance to indentation. The palf fiber composites registered the lowest values at all levels implying that the pineapple fiber produces soft materials as compared to sisal fiber.

The composites incorporated with glass fiber showed higher hardness values in all fiber systems tested. The hardness values increased with increasing fiber content with the glass/ palf composite registering high increase of 30.3% at 40 wg%t fiber content. This suggests that the fiber content has an influence on the hardness of the composites.

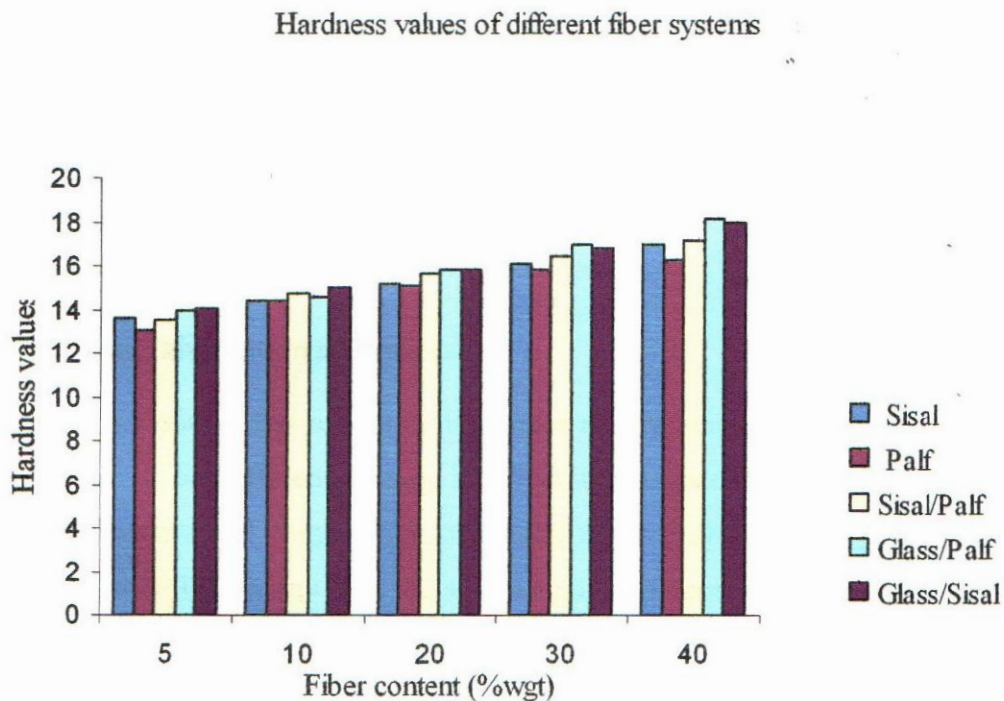


Figure 4.5 Hardness values of modified natural fiber composites

Table 4.2 Hardness values of fiber combinations tested

Fiber content %	Sisal	Palf	Sisal/Palf	Glass/Palf	Glass/Sisal
5	13.58	13.08	13.5	13.94	14.04
10	14.4	14.36	14.72	14.6	15.02
20	15.24	15.1	15.62	15.84	15.82
30	16.08	15.84	16.48	17	16.8
40	16.94	16.24	17.16	18.16	17.92

4.3 Physical properties

Water absorption is generally considered to be disadvantageous as the water uptake can lead to the dimensional instability of composites.

4.3.1 Water absorption of composites

Figure 4.6 shows the results of the water absorption tests. Water absorption levels were noted to be different among the fiber types tested. This discrepancy could be attributed to chemical composition of natural fibers. Tajvidi *et al*, (2005) concluded in their study that fiber composites are significantly different from each other as far as their water uptake is concerned.

Water absorption for different fibers

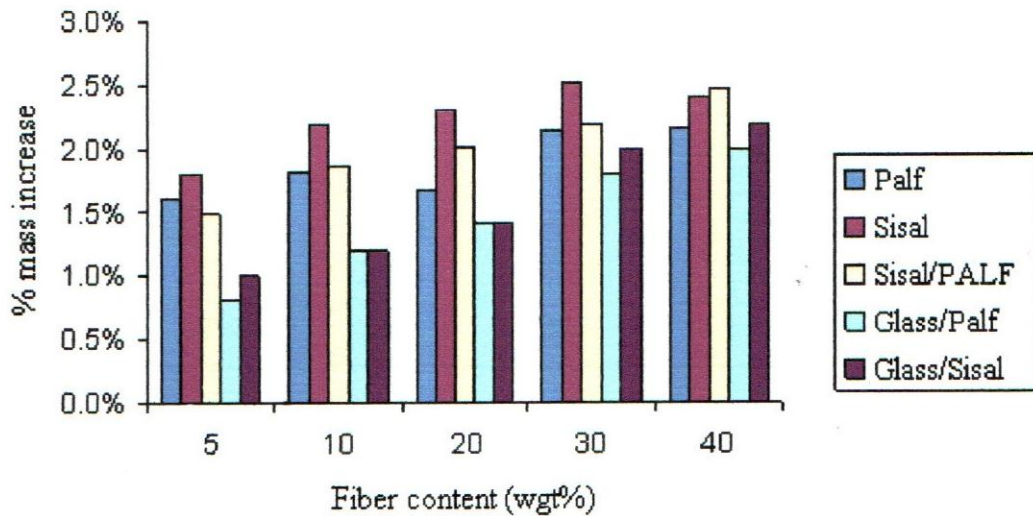


Figure 4.6 Water absorption of composites

The composites having glass fibers registered the lowest water uptake across all per cent mass. This suggests that incorporating glass fibers into the natural fiber improves its dimensional stability. This observation agrees with findings from Rai and Priya, (2006) who reported that the water uptake of hybrid composites were less than that of unhybridized composites. They observed that silk, being a natural fiber has the capacity to absorb moisture though the absorption of moisture is less compared to other natural fibers. And when water-impermeable glass fabric is added to the natural fiber, it acts like a barrier to the fiber, preventing direct contact between it and water.

Table 4.3 shows the mass increase among the fibers tested. These results showed a general increase in mass as the fiber content was increased. Similar observations were made by Hargitai *et al*, (2006) who reported in their study that the mass increase was significantly dependent on fiber content. The glass/palf hybrid composites registered the lowest increase among the various fibers tested. The results indicate that the sisal/ palf composite absorbed more water when compared with the composite samples of sisal and palf alone. In his study Siaotong, (2006) concluded that the chemical treatment of the fibers was effective in decreasing the water absorption capacity of the flax fibers and

concluded that the high mass increase of the treatments with 25% fiber content was not the water absorption capacity of the fibers present but, instead, the porosity of the composites.

Table 4.3 Percentage increase in mass

%Fiber content	Palf	Sisal	Sisal/Palf	Glass/Palf	Glass/Sisal
5	1.6%	1.8%	1.5%	0.8%	1.0%
10	1.8%	2.2%	1.9%	1.2%	1.2%
20	1.7%	2.3%	2.0%	1.4%	1.4%
30	2.1%	2.5%	2.2%	1.8%	2.0%
40	2.2%	2.4%	2.5%	2.0%	2.2%

4.3.2 The thickness swelling of composites

Results for thickness swelling showed the natural fiber composites increasing in thickness more than the composites incorporated with glass fibers as observed in table 4.4 and figure 4.7. The sisal/palf hybrid composites showed the greatest increase in thickness among all the compositions tested. This could be attributed to the chemical composition of the combined natural fibers. Najafi and Najafi (2008) concluded in their study of rice hulls and sawdust that the composites containing rice hull exhibit significantly lower maximum thickness swelling than those made of sawdust. Generally, the hydrophilic nature of lignocellulosic fibers causes the thickness swelling in composites.

Table 4.4 Percentage increase in thickness

Percentage increase in thickness

%Fiber content	Palf	Sisal	Sisal/Palf	Glass/Palf	Glass/Sisal
5	1.6%	1.8%	1.8%	1.2%	1.0%
10	1.8%	2.0%	2.0%	1.4%	1.2%
20	2.0%	2.2%	2.4%	1.0%	1.4%
30	2.4%	2.2%	2.2%	1.4%	1.4%
40	2.2%	2.0%	2.6%	1.2%	1.2%

Thickness swelling increases with immersion time, reaching a certain value where no more thickness swelling is observed reported Najafi and Najafi (2008). They also concluded that temperature had a significant effect on the swelling rate. The swelling rate increased as the temperature increased.

Swelling of fibers can lead to micro-cracking of the composite and degradation of mechanical properties. This problem can be overcome by treating these fibers with suitable chemicals to decrease the hydroxyl group in the fibers. Stamboulis et al. (2000) reported that the moisture absorption and swelling of the treated flax fiber composites is approximately 30% lower than that of composites based on untreated flax fibers.

This could be due its high crystalline fibrils content and thus can share the load applied in matrix. It is observed that the flexural strength increased from 33.36MPa to 54.17MPa representing 62.4% for palf fiber co mposites at 30% fiber content. The reason attributed to this is the increase of fiber-to-fiber interaction and dispersion problem in matrix. The strength characteristics were observed to be dependent on type of fiber used..

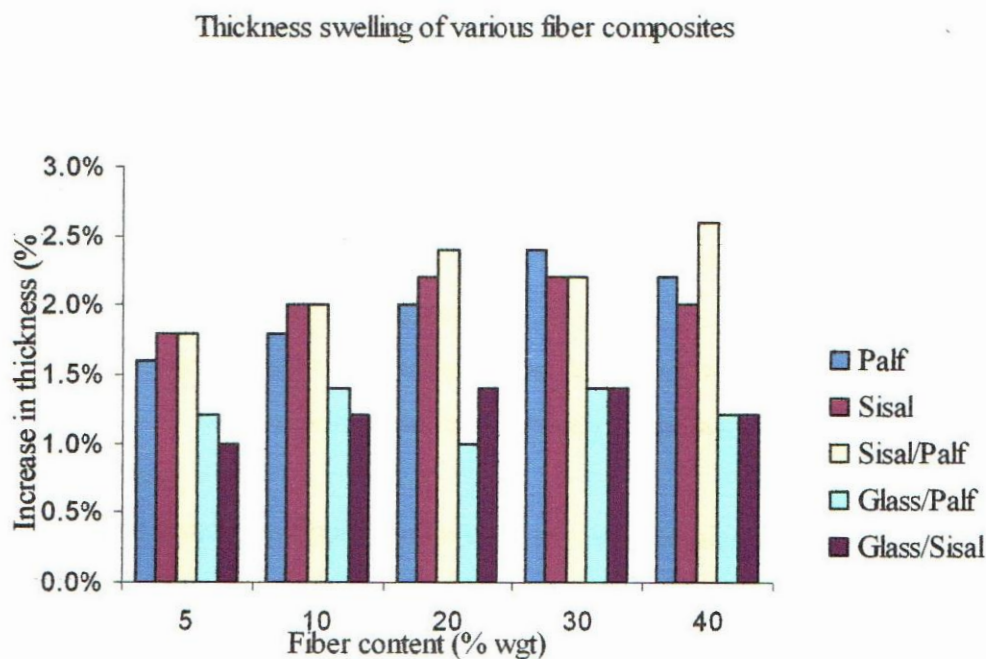


Figure 4.7: Thickness swelling of different fibers

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The results of this study showed that useful composites with good properties could be successfully developed using treated palf and sisal as reinforcing agent for thermoset resin matrices. Recent interest in reducing the environmental impact of materials has led to the development of newer materials or composites that can reduce stress to the environment. In light of petroleum shortages and pressures to decrease the dependence on petroleum products, there is an increasing interest in maximizing the use of renewable materials. The use of agricultural resources as source of raw materials to the industry not only provides a renewable source, but could also generate a non-food source of economic development for farming and rural areas. Appropriate research and development in the area of agricultural based fillers/fibers filled plastics could lead to new value-added, non-food uses of agricultural materials.

- The fiber content in composites has an influence in its mechanical and physical properties. Palf showed that it can withstand greater bending forces than sisal fibers.
- Chemical modification of the sisal and pineapple fibers improved the surface properties of the fibers which translate to improved fiber – matrix adhesion noted in the improved composite properties. The mechanical properties, moisture resistance and biodegradation are improved by surface modification of fibers.
- The use of natural fibers in composite manufacture could be limited by water absorption which results in dimensional instability of the composites and poor surface adhesion to hydrophobic polymers.
- It was observed that water uptake was dependent on fiber content. The high water uptake has been reported to significantly influence the composites' mechanical properties.
- Sisal and pineapple fibers can be used to reinforce plastics due to their low cost, high specific strength and biodegradability. These fibers can also be used in the preparation of hybrid composites with synthetic fibers such as glass fiber so as to reduce the cost of the products.

In view of the results obtained in this study it can be concluded that the composites from sisal, pineapple and their glass fiber hybrids in polyester matrix can find application in the building, automotive industries and for recreational facilities.

5.2 Recommendations

This study may be more applicable and better if the following suggestions are undertaken:

- The work should be extended to study other properties such as impact, shear strength, chemical resistance and electrical properties.
- More studies on locally available plant fibers, especially the agricultural wastes should be undertaken so as to add value to the farm produce and enhance the country's economy and subsequently increase the farmers' standard of living.
- Besides the polyester resin, other polymeric matrix systems eg. phenolic and epoxy could be incorporated into the fibers and the properties of the resulting composites studied. This could result in a more inexpensive product having good adhesion properties which can then serve the building industry for a developing country like Kenya.
- Studies be extended into the naturally occurring plant resins eg. tannin, soy bean and cashew nut shell liquid with a view to coming up with a purely bio-degradable composite for a cleaner environment.
- Hybrid composite comprising other fibers besides palm and sisal can be studied in the search for composites that can yield better performance which is competitive with the conventional synthetic fibers

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APPENDICES

Appendix A Bending strength tests table

TEST/F.C	5%	10%	20%	30%	40%
Palf					
T1	33.33	41.7	47.5	53.57	48.30
T2	32.7	40.45	48.01	54.6	49.27
T3	34.54	39.86	47.81	54.73	47.96
T4	33.5	41.41	48.11	53.84	47.73
T5	33.73	40.71	47.52	54.11	49.02
MEAN	33.56	40.826	47.79	54.17	48.46
SD	3.178	3.996	2.385	0.937	0.67
C. V	9.53%	9.84%	5.02%	1.73%	1.38%
Sisal					
T1	32.03	37.71	45.37	51.45	47.67
T2	31.65	38.01	45.06	50.98	48.03
T3	31.78	37.95	45.61	51.82	47.87
T4	32.01	38.03	44.98	51.25	48.01
T5	30.98	37.89	45.34	51.79	47.99
MEAN	31.69	37.918	45.272	51.458	47.91
SD	0.428	0.129	0.254	0.358	0.15
C. V	1.35%	0.34%	0.56%	0.70%	0.31%
Sisal/Palf					
T1	40.37	48.19	56.73	65.21	61.87
T2	41.00	48.78	55.25	66.69	62.16
T3	40.98	47.32	55.43	66.84	62.00
T4	40.73	46.99	54.95	67.12	62.59
T5	39.83	47.62	55.41	66.14	62.37
MEAN	40.58	47.78	55.55	66.4	62.20
SD	0.49	0.712	0.68	0.75	0.29
C. V	1.21%	1.49%	1.23%	1.14%	0.46%
Glass / Sisal					
T1	43.33	50.49	57.67	69.49	65.71
T2	42.96	50.39	57.21	69.03	65.87
T3	42.99	50.47	56.96	68.92	66.09
T4	43.07	50.46	57.04	69.01	66.13
T5	43.28	50.36	56.98	68.97	65.88
MEAN	43.13	50.43	57.17	69.08	65.94
SD	0.169	0.056	0.295	0.231	0.173
C. V	0.39%	0.11%	0.52%	0.33%	0.26%
Glass / Palf					
T1	46.73	54.08	61.18	70.87	67.37
T2	46.25	54	61.16	70.11	66.91
T3	45.91	54.03	60.95	70.04	67
T4	46.08	53.99	61.03	69.99	67.95
T5	45.89	54.12	61	69.96	67.4
MEAN	46.17	54.04	61.06	70.19	67.33
SD	0.34	0.06	0.10	0.38	0.41
C. V	0.75%	0.10%	0.17%	0.54%	0.61%

s = Standard deviation called sigma

$\bar{X}$ = The mean of the tests.

$$C.V. = \frac{s}{\bar{X}}$$

T_i = The value of the ith test in the series

Appendix B Hardness Tests Table

TEST/F.C	5%	10%	20%	30%	40%
Palf					
T1	13.4	14.2	15.5	16.1	17.1
T2	13.1	14.4	15.3	15.7	16.9
T3	12.8	14.6	14.9	15.6	17
T4	12.9	14.7	15	16	16.86
T5	13.2	13.9	14.8	15.8	17.3
MEAN	13.08	14.36	15.1	15.84	17.032
SD	0.239	0.321	0.292	0.207	0.176
C. V	1.83%	2.23%	1.93%	1.31%	1.04%
Sisal					
T1	13.8	14.4	15.3	16.1	17
T2	13.7	14.6	15.4	16.2	17.1
T3	13.4	14.3	15.2	16	16.8
T4	13.4	14.2	15.1	16	16.9
T5	13.6	14.5	15.2	16.1	16.9
MEAN	13.58	14.4	15.24	16.08	16.94
SD	0.179	0.158	0.114	0.084	0.114
C. V	1.32%	1.10%	0.75%	0.52%	0.67%
Glass/Palf					
T1	13.9	15	15.7	17.1	18
T2	13.9	14.6	15.8	16.8	18.8
T3	13.8	14	15.8	17	17.9
T4	14	14.6	16	16.9	18.4
T5	14.1	14.8	15.9	17.2	17.7
MEAN	13.94	14.60	15.84	17.00	18.16
SD	0.11	0.37	0.11	0.16	0.44
C. V	0.82%	2.56%	0.72%	0.93%	2.42%
Sisal/Palf					
T1	13.6	14.8	15.4	16.8	17.2
T2	13.3	14.6	15.6	16.2	17.3
T3	13.9	14.8	15.8	16.4	17.1
T4	13.4	14.8	15.7	16.7	17
T5	13.3	14.6	15.6	16.3	17.2
MEAN	13.5	14.72	15.62	16.48	17.16
SD	0.25	0.11	0.15	0.26	0.11
C. V	1.89%	0.74%	0.95%	1.57%	0.66%
Glass/Sisal					
T1	14.1	15	15.8	16.6	17.8
T2	13.9	14.9	15.9	16.9	17.8
T3	14	14.9	15.7	16.8	18.1
T4	14	15.1	15.8	16.8	17.9
T5	14.2	15.2	15.9	16.9	18
MEAN	14.04	15.02	15.82	16.8	17.92
SD	0.11	0.13	0.08	0.12	0.13
C. V	0.81%	0.87%	0.53%	0.73%	0.73%

s = Standard deviation called sigma

$$C.V. = \frac{s}{\bar{X}}$$

$\bar{X}$ = The mean of the tests.

T_i = The value of the ith test in the series

Appendix C Thickness Swelling Test Table

TEST/F.C	5%	10%	20%	30%	40%
Thickness of palf sample composite before immersion					
T1	0.51	0.97	1.36	1.69	2.03
T2	0.48	0.98	1.37	1.69	2.04
T3	0.47	0.97	1.35	1.68	2.02
T4	0.5	0.99	1.37	1.7	2.02
T5	0.46	0.98	1.35	1.69	2.04
MEAN	0.484	0.978	1.36	1.69	2.03
SD	0.022	0.009	0.010	0.009	0.010
C. V	4.50%	0.94%	0.74%	0.51%	0.49%
Thickness of palf Sample composite after immersion					
T1	0.53	0.98	1.39	1.71	2.06
T2	0.5	0.99	1.38	1.72	2.06
T3	0.48	1	1.38	1.69	2.05
T4	0.51	1.01	1.39	1.72	2.03
T5	0.48	1	1.36	1.73	2.06
MEAN	0.5	0.996	1.38	1.714	2.052
SD	0.023	0.011	0.012	0.019	0.012
C. V	4.69%	1.12%	0.89%	1.11%	0.61%
Thickness of Sisal sample composite before immersion					
T1	0.69	1.11	1.5	2.3	2.53
T2	0.7	1.12	1.49	2.31	2.5
T3	0.68	1.09	1.53	2.35	2.52
T4	0.69	1.1	1.55	2.34	2.51
T5	0.7	1.13	1.52	2.3	2.53
MEAN	0.692	1.11	1.518	2.32	2.518
SD	0.009	0.018	0.020	0.027	0.009
C. V	1.37%	1.62%	1.33%	1.18%	0.38%
Thickness of Sisal sample composite after immersion					
T1	0.71	1.13	1.51	2.34	2.55
T2	0.73	1.13	1.52	2.33	2.52
T3	0.69	1.11	1.55	2.36	2.55
T4	0.71	1.13	1.58	2.35	2.53
T5	0.71	1.15	1.54	2.33	2.54
MEAN	0.71	1.13	1.54	2.342	2.538
SD	0.014	0.017	0.026	0.015	0.011
C. V	1.99%	1.53%	1.69%	0.63%	0.44%
Thickness of Sisal/Palf sample composite before immersion					
T1	0.6	1.01	1.67	2.12	2.63
T2	0.58	1.02	1.65	2.1	2.64
T3	0.59	1.01	1.65	2.15	2.62
T4	0.57	1.03	1.67	2.13	2.63
T5	0.61	1.02	1.69	2.14	2.64
MEAN	0.59	1.018	1.666	2.128	2.632
SD	0.015	0.009	0.017	0.017	0.009
C. V	2.54%	0.91%	1.00%	0.81%	0.36%

s = Standard deviation called s

$\bar{X}$ = The mean of the tests.

$$C.V. = \frac{s}{\bar{X}}$$

T_i = The value of the ith test in the series

Appendix C Thickness swelling Test cont'd

Thickness of Sisal/Palf sample composite after immersion

T1	0.61	1.03	1.69	2.14	2.66
T2	0.6	1.04	1.68	2.13	2.66
T3	0.61	1.04	1.66	2.17	2.65
T4	0.59	1.05	1.71	2.15	2.65
T5	0.63	1.03	1.71	2.16	2.67
MEAN	0.608	1.038	1.69	2.15	2.658
SD	0.014	0.008	0.025	0.016	0.009
C. V	2.35%	0.81%	1.51%	0.74%	0.35%

Thickness of Glass/Palf composite sample before immersion

T1	1.54	2.11	2.63	3.13	3.54
T2	1.55	2.12	2.61	3.11	3.52
T3	1.62	2.11	2.58	2.99	3.5
T4	1.54	2.13	2.6	3.01	3.51
T5	1.51	2.09	2.59	2.95	3.47
MEAN	1.55	2.11	2.60	3.04	3.51
SD	0.05	0.01	0.02	0.07	0.03
C. V	3.42%	0.68%	0.84%	2.42%	0.73%

Thickness of Glass/Palf composite sample after immersion

T1	1.55	2.13	2.64	3.14	3.55
T2	1.56	2.14	2.62	3.13	3.53
T3	1.63	2.11	2.59	3.01	3.51
T4	1.54	2.14	2.61	3.02	3.52
T5	1.53	2.1	2.6	2.96	3.49
MEAN	1.56	2.12	2.61	3.05	3.52
SD	0.052	0.018	0.022	0.072	0.022
C. V	3.34%	0.84%	0.83%	2.36%	0.64%

Thickness of Glass/sisal composite sample before immersion

T1	1.61	2.17	2.64	3.18	3.58
T2	1.58	2.2	2.65	3.2	3.55
T3	1.56	2.18	2.66	3.15	3.5
T4	1.59	2.21	2.67	3.21	3.54
T5	1.63	2.16	2.65	3.1	3.53
MEAN	1.594	2.184	2.654	3.168	3.54
SD	0.031	0.019	0.012	0.042	0.035
C. V	1.95%	0.88%	0.44%	1.34%	0.99%

Thickness of Glass/sisal composite sample after immersion

T1	1.62	2.18	2.66	3.19	3.6
T2	1.6	2.21	2.68	3.22	3.56
T3	1.57	2.2	2.66	3.16	3.51
T4	1.6	2.22	2.68	3.22	3.55
T5	1.63	2.17	2.66	3.12	3.54
MEAN	1.604	2.196	2.668	3.182	3.552
SD	0.029	0.020	0.010	0.040	0.039
C. V	1.78%	0.89%	0.37%	1.25%	1.09%

s = Standard deviation called sigma

$\bar{X}$ = The mean of the tests.

$$C.V. = \frac{s}{\bar{X}}$$

T_i = The value of the ith test in the series

Appendix D Water Absorption Test Table

TEST/F.C	5%	10%	20%	30%	40%
Weight of palf composite sample before immersion					
T1	1.96	2.38	2.8	3.37	3.91
T2	1.94	2.38	2.83	3.36	3.87
T3	1.96	2.37	2.78	3.36	3.89
T4	1.94	2.37	2.81	3.39	3.9
T5	1.96	2.4	2.79	3.4	3.93
MEAN	1.95	2.38	2.80	3.38	3.90
SD	0.01	0.01	0.02	0.02	0.02
C. V	0.51%	0.56%	0.61%	0.54%	0.44%
Weight of palf composite sample after immersion					
T1	1.98	2.43	2.89	3.42	3.99
T2	1.96	2.42	2.88	3.47	3.98
T3	1.99	2.42	2.84	3.46	3.99
T4	1.98	2.44	2.84	3.43	3.98
T5	2.01	2.41	2.8	3.47	3.99
MEAN	1.98	2.42	2.85	3.45	3.99
SD	0.01	0.01	0.03	0.02	0.01
C. V	0.70%	0.47%	1.16%	0.63%	0.13%
Weight of Glass/Sisal composite sample before immersion					
T1	2.52	3.01	3.54	3.91	4.31
T2	2.51	3.03	3.53	3.9	4.3
T3	2.51	3.01	3.54	3.92	4.33
T4	2.53	2.99	3.51	3.94	4.31
T5	2.5	3	3.53	3.92	4.34
MEAN	2.51	3.01	3.53	3.92	4.32
SD	0.01	0.01	0.01	0.01	0.02
C. V	0.45%	0.33%	0.37%	0.30%	0.35%
Weight of Glass/Sisal composite sample after immersion					
T1	2.53	3.02	3.56	3.92	4.33
T2	2.52	3.03	3.54	3.93	4.34
T3	2.52	3.02	3.55	3.94	4.35
T4	2.54	3.02	3.53	3.95	4.33
T5	2.51	3.01	3.54	3.95	4.35
MEAN	2.52	3.02	3.54	3.94	4.34
SD	0.01	0.01	0.01	0.01	0.01
C. V	0.45%	0.17%	0.33%	0.32%	0.26%
Weight of Glass/palf composite sample before immersion					
T1	2.41	2.78	3.1	3.59	4.03
T2	2.38	2.76	3.13	3.57	4.01
T3	2.4	2.8	3.11	3.61	3.99
T4	2.43	2.77	3.15	3.58	4.02
T5	2.42	2.78	3.16	3.6	4.02
MEAN	2.408	2.778	3.130	3.590	4.014
SD	0.014	0.016	0.027	0.016	0.019
C. V	0.57%	0.58%	0.87%	0.44%	0.48%

s = Standard deviation called sigma

$\bar{X}$ = The mean of the tests.

$$C.V. = \frac{s}{\bar{X}}$$

T_i = The value of the ith test in the series

Appendix D Water Absorption Test

Weight of Glass/palf composite sample after immersion

T1	2.42	2.79	3.12	3.61	4.05
T2	2.39	2.78	3.14	3.59	4.03
T3	2.4	2.81	3.12	3.63	4.02
T4	2.43	2.78	3.17	3.59	4.04
T5	2.44	2.79	3.17	3.62	4.03
MEAN	2.416	2.790	3.144	3.608	4.034
SD	0.018	0.015	0.028	0.019	0.013
C. V	0.75%	0.54%	0.88%	0.53%	0.33%

Weight of sisal composite sample before immersion

T1	1.88	2.4	2.89	3.4	3.9
T2	1.9	2.39	2.87	3.45	3.91
T3	1.89	2.4	2.87	3.43	3.88
T4	1.87	2.41	2.9	3.42	3.94
T5	1.87	2.4	2.91	3.4	3.93
MEAN	1.882	2.4	2.888	3.42	3.912
SD	0.010	0.005	0.018	0.016	0.029
C. V	0.54%	0.21%	0.62%	0.46%	0.73%

Weight of sisal composite sample after immersion

T1	1.9	2.46	2.95	3.5	4.01
T2	1.92	2.44	2.96	3.52	4.01
T3	1.9	2.46	2.95	3.51	3.99
T4	1.89	2.46	2.95	3.5	4.02
T5	1.89	2.45	2.97	3.51	4.01
MEAN	1.9	2.454	2.956	3.508	4.008
SD	0.007	0.006	0.009	0.006	0.014
C. V	0.37%	0.26%	0.31%	0.17%	0.35%

Weight of sisal/palf composite sample before immersion

T1	2.38	2.61	3.13	3.82	4.04
T2	2.37	2.62	3.14	3.86	4.02
T3	2.37	2.66	3.09	3.82	4.03
T4	2.38	2.61	3.1	3.85	4.02
T5	2.39	2.65	3.07	3.87	4.05
MEAN	2.378	2.63	3.106	3.844	4.032
SD	0.008	0.027	0.025	0.025	0.012
C. V	0.35%	1.04%	0.79%	0.64%	0.29%

Weight of sisal/palf composite sample after immersion

T1	2.42	2.69	3.19	3.96	4.14
T2	2.42	2.69	3.18	3.9	4.13
T3	2.4	2.68	3.15	3.95	4.13
T4	2.42	2.66	3.16	3.91	4.13
T5	2.41	2.68	3.17	3.93	4.14
MEAN	2.414	2.68	3.17	3.93	4.134
SD	0.011	0.011	0.018	0.023	0.005
C. V	0.45%	0.42%	0.57%	0.58%	0.13%

s = Standard deviation called sigma

$$C.V. = \frac{s}{\bar{X}}$$

$\bar{X}$ = The mean of the tests.

T_i = The value of the ith test in the series

Appendix E: Equipment used for various tests



Figure 3.8 Oven with samples for drying

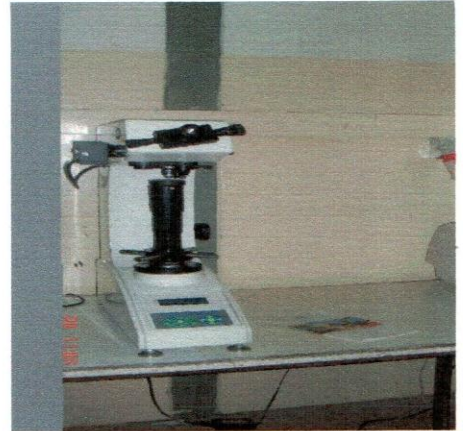


Figure 3.9 The Vickers hardness tester 430/450



Figure 3.10 The hydraulic Universal Material Tester 50 kN (WP 310) machine

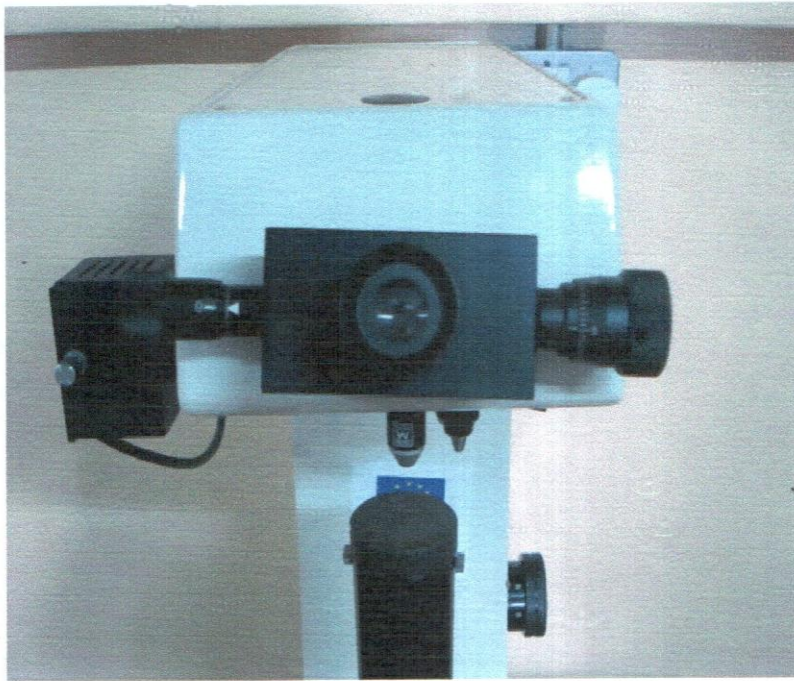


Figure 3.11. The measuring microscope complete with micrometer, eyepiece, indenter anvil and positioning knob of the Vickers hardness tester.



Figure 3.12 The composite sample being pressed

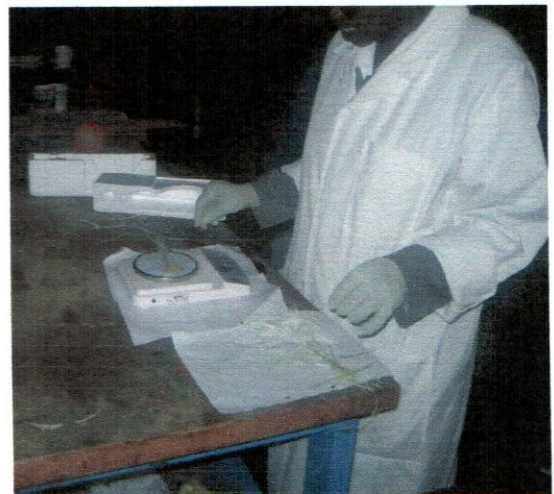


Figure 3.13 The weighing process of the fibers on the electronic balance

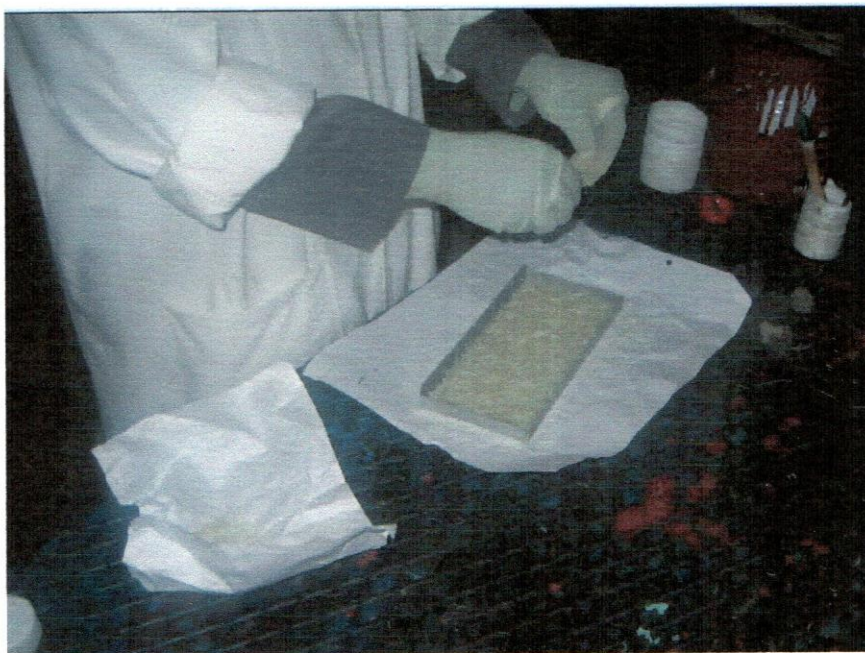


Figure 3.14 The hand laying process of the fibers

