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REVIEW OF THE HISTORY, PROPERTIES AND APPLICATION OF PLANT FIBRES

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ABSTRACT:- *A complete survey of natural fibres that includes a discussion of all the different classifications of plant fibres would include far too much material for one article so some of the commercially important fibres have been selected for consideration. Although there is no profound relationship between the origin of fibres and their mechanical properties, bast fibres possess the lowest microfibril angle and, on average, best mechanical properties. Physical and mechanical properties of plant fibres differ from one type to another leading to differences in end use performance. There is a strong relationship between the fine structure of plant fibres and their mechanical properties. Plant fibres are an alternative resource to synthetic fibres as reinforcement for polymeric materials for the manufacture of cheap, renewable and environmentally friendly composites.*

Keywords: *Plant fibres, cellulosics, properties, applications*

INTRODUCTION

Cellulose is a skeletal polysaccharide, ubiquitous in the plant kingdom and one of the commonest naturally occurring fibrous materials. Strictly speaking all plant fibres are single-cell materials. Except for seed fibres most plant fibres exist in bundles of ultimate fibres. A fibre is defined as 'a unit of matter characterised by flexibility, fineness, and high ratio of length to thickness' while fibre ultimate can be defined as 'one of the unit botanical cells into which leaf and bast fibres can be distinguished' [1,2]. The use of these naturally occurring cellulosic fibres can be traced back more than 10,000 years. About 8,000 B.C. in the Middle East and China the cellulosics were used for textiles [3]. For instance, clothing made of flax fibres has been traced back to around 3000 B.C. and the Babylonians used flax fibre for burial purposes in about 650 B.C. [4]. The use of plant fibres as reinforcement materials dates back to prehistoric times when straw was put into bricks during the reign of Pharaoh. The Inca and Maya made similar plant fibre reinforced pottery [5]. In the 1930s Henry Ford constructed an entire automobile body from hemp and presently automobile manufactures such as BMW and Mercedes are beginning to incorporate hemp into car components [3]. The applications of fibres covered in this article range from apparel and ornamental fabrics to industrial materials. To simplify the discussion the selected fibres have been split into three main class groups arranged according to their morphological structure, namely: (a) bast fibres- those produced from plant stems, (b) leaf fibres- those produced from the leaves of plants, and (c) seed hair fibres, which for the purpose of convenience will include fruit fibres. Table 1 shows the classification of the selected plant fibres, the world annual production and cost.

Table 1 shows that cotton fibre is the most abundant followed by bamboo, jute and kenaf respectively while abaca fibre is the least abundant. The application of cotton is mainly in the apparel while the rest could easily be used in the composite manufacture and are of special interest in this review

The aim of this survey is to describe the historical use of plant fibres, methods of extraction and/or separation, physical and mechanical properties, and to discuss future end uses for these fibres.

Table 1: Classification of plant fibres, origin, world annual production and cost

Fibre type	Botanical name	Plant origin	Production (10^3 Tonnes)	Cost ($/kg)	[Source]
Abaca	*Musa textilis*	Leaf	91		6,7,8,9
Bagasse	*Saccharum officinarum L*	Stem	102,000		6,7,9,10,11
Banana	*Musa ulugurensis* Warb.	Leaf	200	0.1	6,7,9
Bamboo	*Gigantochloa scortechinii* *Dendrocalamus apus*	Stem	10000		9
Coir	*Cocos nucifera L.*	Fruit	650	0.84	6,8,10,12
Cotton	*Gossypium spp.*	Seed	19010	2	8,9
Flax	*Linum usitatissimum*	Stem	830	0.6-0.8	13,14,8,9,15
Hemp	*Cannabis sativa* L.	Stem	214	0.7-0.8	8,9,15
Jute	*Corchorus capsularis, Corchorus olitorius*	Stem	2850	0.8-0.9	12,15
Kapok	*Ceiba pentandra*	Seed	123	0.2	12
Kenaf	*Hibiscus cannabinus*	Stem	970	0.7-0.8	8,9,15
Phormium	*Phormium tenax*	Leaf	-		16
Pineapple	*Ananas cosmosus* Merr.	Leaf	-		12
Ramie	*Boehmeria nivea* Gaud	Stem	100		8,15
Sisal	*Agave sisilana*	Leaf	318.8	0.74	6,8,9,11

Fibre Types

Fibres originating from the bast stem, leaf and fruit are naturally organised into bundles and are therefore called fibre bundles, whereas fibres originating from seed are single cells and are referred to as fibres [1, 17]. The processes used to separate fibre bundles from the bast stem and leaf is quite similar. Seed fibres, especially cotton lint, are separated from the seed by the ginning process while kapok fibres are separated by shaking as they are loosely held to the seed. Decortication and retting techniques are usually employed to separate fibres bundles from the leaf and bast of fibre plants. The size of the bundle is governed by the severity of the process. A decorticator is a machine used to strip fibre bundles from the stem or leaf. Leaves are crushed and beaten by a rotating wheel set with blunt knives so that only the fibres remain. The other parts of the leaf are washed away by water. Decorticated fibres are then washed before drying on the sun or using hot air. The dry fibres are combed and sorted into various grades [18]. Retting is defined as 'the subjection of crop or deseeded straw to chemical or biological treatment to make the fibre bundles more easily separable from the woody part of the stem' [1] to facilitate the removal of fibre bundles. There are two traditional types of retting namely dew and water retting. Dew retting entails leaving the plant stem in the field to rot. In this process retting is constantly monitored to ensure that bast fibres separate from the core without much deterioration in quality. Dew retting is the most popular in Europe although it is heavily dependent on the geographical location, produces coarser and lower quality fibres than those produced using water retting technique [19]. Water retting entails the soaking of stems in water (ponds or tanks and slow moving rivers). Water retting may require large amount of clean water and therefore expensive but results in high quality fibres and produces environmentally unacceptable fermentation waste.

A concise history and discussion of the physical and mechanical properties of the plant fibres listed in Table 1 follows. The relationship between fine structure and mechanical properties is described. Recent developments in plant fibre reinforced composites are also discussed.

Fruit fibre

Coir fibre has been used in India for about 3000 years. The name coir is derived from the Malayalam *kayaru*, 'cord' [20]. It is grown in the Indo-Malaysian region, East and Western African countries, and Central and South America. It is obtained from the fruit of the coconut palm and the fibrous tissue lies between the exocarp and the endocarp surrounding the kernel. There are three types of coconut fibre, namely the longest and the finest called 'white' fibre, a coarser fibre known as 'brittle' fibre, and a shorter staple fibre known as 'mattress' [21]. The brittle and mattress fibres are often referred to as 'brown' fibre [22, 23]. The retting process is traditionally employed to extract coir fibre bundles where the husk is immersed in water for 3-9 months. The decorticating process can also be used to separate the fibre bundles.

Leaf fibres

The leaf fibres, also referred to as 'hard' fibres, are obtained from the leaves or leaf stalks of various monocotyledonous plants. Monocotyledons have parallel veined leaves and have one seed leaf [22]. Abaca fibre is the most important species of the Musaceae plant family. It resembles the *Musa ulugurensis*, which bears the edible banana fruit and produces high quality fibres. The fibres are in bundles of individual cells obtained from the leaf sheaths. They are removed from the strands by boiling in an alkali solution and are smooth with uniform diameter. The fibre lumen is large in relation to the cell wall.

Banana fibre *Musa paradiisiaca* L. var *Sapientum* or *Musa ulugurensis* Warb. is the most cultivated banana plant. The word banana comes from Arabic and it means 'finger' [24]. There are about 300 species of banana and about 20 are used for consumption. In order to obtain the best fibre the plants are cut when they are almost at the flowering stage, before any fruit has formed. The separation process is done manually and it involves cutting pieces of banana from the stem and passing them through a mangle to remove excess moisture (water), and combing and drying at ambient temperature. The fibre obtained is usually of low quality because the separation of the fibre bundles is done either after the fruits have just developed or when they have ripened ready for food purposes.

Phormium otherwise called New Zealand flax is named after the Greek phormos 'basket' because that was one of the early main uses of the fibre [20]. In Europe it was grown for its leaves and in the past it was used for ornamental purposes. It is extracted mechanically, hand prepared and woven into cloth resembling linen.

Pineapple plants are largely grown in tropical America, in the Far-East Asia countries and Africa. It is in the Philippines and Taiwan where the pineapple plant is largely used as a source of fibre. India also uses the pineapple plant as a source of fibre. The pineapple fibre bundles are separated from the pineapple leaf by hand and sometimes by machines. The hand separation involves the stripping off of the fibre from the retted leaf. This method is considered to be laborious and costly and tends to lose a lot of weaker fibres. The use of machines to separate the fibre bundles is slower than the hand method of extraction but facilitates production processes. The yield of hand separated pineapple fibre bundles is in the range 2% to 3% dry fibre from about 1 tonne of pineapple leaf, that is, 20 kg to 27 kg of dry fibre [25].

The agave genus includes more than 250 species. Sisal is a semi-xerophyte plant practically without a stalk from which fibre is obtained. Major sisal fibre growing countries are Brazil, Tanzania, and Kenya [6]. Sisal is distinguished from abaca by Billinghame's test and the presence of rod-like crystals in the ash. It differs from phormium fibre in that the ultimate fibres are polygonal in outline with a rounded polygonal lumen when viewed in cross-section. The lumen varies in size but is usually large and well defined and the longitudinal shape is approximately cylindrical with a blunt tapering tip. In general the fibre characteristics are similar to those of abaca [20].

Bast stem fibres

Bast fibres are obtained from the stems of various dicotyledonous plants and are also referred to as 'soft' fibres to distinguish them from leaf fibres. Dicotyledons are plants with two seed leaves cotyledons. Botanically the term bast (bark) is synonymous with phloem, the food conducting tissue of vascular plants. It is also used to denote fibres obtained from the cortex and pericycle in addition to the phloem. Bast fibre bundles are composed of elongated thick-walled ultimate cells joined together both end to end and side by side and arranged in bundles along the length of the stem. Bast fibre bundles are removed from the parent material by the decorticating process, which consists of removing from the stem, the 'cortex' comprising the bast and outer barks. The separated fibres are then washed in water and dried.

Bamboo has a hollow stem called the culm with the cellulose fibres aligned along the length of the culm carrying nutrients between the leaves and roots. It has a light coloured lignin. Bamboo can be grown in both the tropics and in temperate climates. There are over 1,250 species of bamboo and over 10, 000 tonnes are produced annually [8]. It is one of the main building materials used in developing countries, surpassed only by wood.

Flax can be grown and harvested in just three months time. The fully-grown flax plant is about 900-1200 mm long and 1.5-3 m wide. It is grown in such a way that harvesting must take place before lignifications takes place as this will result in poor quality fibre. However, early harvesting produces a low yield of fibre. The fibre is produced mainly in temperate climates. The number of fibre bundles in the stem ranges from 15 to 40 and each bundle contains between 12 and 40 ultimate fibres. The ultimate fibres consist of pointed cells with very thick walls and very small lumens. Flax, unlike other bast fibres, contains transverse dislocations often in the form of an X [22].

Hemp is a temperate climate plant grown mainly in Russia and Eastern Europe. The Chinese have used hemp for at least 6,000 years. The fibre was first planted in North America in 1606 by French botanist Louis Hevert. Hemp was formally christened *Cannabis sativa* L. in 1753 by Swedish botanist Carl Linnaeus [3]. However, it worth noting that *Cannabis sativa* is usually confused with the marijuana plant. In contrast to the industrial hemp, which is planted only centimetres apart with most of its leaves concentrated at the top, the mariajuana plant is quite dense, leafier, shorter, bushier, and is planted meters apart. From as early as 5 B.C. to the mid-1800s hemp fibres were used to manufacture 90% of all ships' canvas sails, rigging, nets, and caulk because of its strength and resistance to salt water [3]. It is reported that the hemp plant will produce about 0.168 kg of fibre per square meter whereas the cotton plant will produce only 0.057 kg of fibre per square meter and hemp does not need the enormous amount of agricultural chemicals that cotton needs to grow. Over a period of 20 years 1m^2 of hemp plants will produce as much pulp as 4m^2 of forestland [3].

Hemp fibre bundles are separated from the stem in a decortication process in which the plant is either cut or pulled from the ground. The cut plant is then retted allowing the enzyme secreted by micro organisms to digest or degrade the non-cellulose materials, mainly pectins, which holds the fibrils together to liberate the fibre bundles [26]. The long bark fibre from the stalk can be spun into threads, made into ropes, woven into fabrics, carpets and shoes and made into canvas. The inner core of stalk or hurd can be made into dioxin-free paper and pulp as well as charcoal, methanol, and methane. The latter are biomass fuels, which are clean and virtually free from pollutants generated by the combustion of fossil fuels.

Jute is the second most important fibre apart from cotton. It is a fast growing annual plant. In hot and humid climate jute plants reach about 2.5 - 3 m in height within 4-6 months. *Corchorus capsularis* has a globular shaped pod whereas *Corchorus olitorius* is cylindrical [25, 27]. Most of the jute is harvested when about 50 % of the plants are in pod because it is during this stage of growth that high quality jute fibre bundles can be obtained. The fibre bundles are separated from the woody stem by the retting process. About 10,000 to 14,000 kgs of green plant yield from 4. 5 - 8 % of their green weights in dry fibre. The fibre lies along the length of the plant stem in the form of an annular meshwork composed of more than one fibre layer. Jute is the most widely produced of the bast fibres followed by flax and hemp fibres. It has a higher lignin content, which distinguishes it from flax and hemp fibres.

Kenaf has been cultivated for 4000 years but has only recently been exploited as a source of fibre. It is grown in tropical and sub-tropical areas. In Brazil it is cultivated throughout the year. The bark fibres of kenaf plant are long and stringy but the inner core is much like balsa wood. Kenaf can produce about 2.47 kg of pulp per season, which is the same amount that a pine tree can produce after 20 years of growth [28]. Application for which kenaf fibres find markets are very similar to those of other bast fibres, namely paper making, pulp and more importantly is its use and in making building materials like fibreboards that are insect, fire and rot proof.

Ramie is obtained from a tall shrub grown in Brazil, India, Japan, South-East Asia, and Southern Europe. The Chinese have grown the fibre for centuries and it is sometimes referred to as 'China' grass [22]. Ramie is a perennial plant and can last for 7-20 years. The fibre can be prepared from pieces of parent root stock and can be harvested 3-6 times a year. The highest yield is attained in the third and fourth years and maintained until the plant is about six years old [29]. The fibre is extracted from the green plant by decorticating processes. Some times a de-gumming treatment such as an alkali boil is used to separate the fibre from the main material. Ramie fibre is easily identified by its coarse, thick walls, lacks twist and has striated surfaces [25].

Seed fibres

The seed fibres are generally formed from a single biological cell. It is reported that more than one cell takes part in the growth of fibres. The most important of the seed fibres is cotton. Cotton is mostly grown in warm temperate and tropical regions, between latitudes 40^o N and 40^o S. The plant was originally a perennial plant but nowadays almost exclusively grows as an annual crop. Cotton fibre has been in use for at least 5000 years. It takes 45-65 days, from the blossom to the open ball, for the fibre to mature. The maturity of cotton fibre is determined by assessing the shape of the wall-thickness as compared to the size of the lumen. Maturity is defined as the ratio, θ, of the cross-sectional area, A, of the cell wall to the area, A_o, of a circle with the same perimeter. Others prefer the reciprocal of the maturity, which is called the Immaturity Ratio, I [30].

Kapok (*Ceiba pentandra*) is reported to occur wild in American tropics and in evergreen, moist, semi-deciduous and gallery forests of West Africa. Kapok is said to have reached Java by the 10th century and that it is the Arab traders who took Kapok from West Africa to India and the Far East. Barker [31] identified three varieties namely; Var. *caribaea*, Var. *guineensis* and Var. *pentandara* synonymous to Var. *indican* (DC) Bakh. Var. *pentandra* is a natural hybrid between Var. *caribeae* and Var. *guineensis* [32]. It is reported that by 1959 India, Kenya, Tanzania and Thailand exported nearly 12,000 tonnes of kapok fibre [25].

Table 2 shows the chemical composition of some plant fibres, and the physical properties of the plant fibres. It is noted that cellulose is the main constituent of plant fibres followed by hemi-celluloses and lignin interchangeably and pectin respectively. Cellulose is also the reinforcement for lignin, hemi-celluloses and pectin [46]. This makes plant fibres exhibit characteristics of a composites material. The physical properties shown in Table 3 are those of the single cell (ultimates) fibres i.e., the physical properties of leaf and bast fibres. Fibres with the highest aspect ratio will exhibit highest tensile properties provide high surface area advantageous for reinforcement purposes.

Table 2: Chemical composition of some plant fibres

Fibre type	Cellulose	Hemicelluloses	Lignin	Pectin	[Source]
Abaca	61-64	21	12	0.8	12,22
Bagasse	32-48	21	19.9-24	10	9,33
Banana	60-65	6-19	5-10	3-5	34
Bamboo	26-43	15-26	21-31	-	9
Coir	46	0.3	45	4	35,36
Cotton	82-96	2-6	0.5-1	5-7	9
Flax	60-81	14-19	2-3	0.9	9,36
Hemp	70-92	18-22	3-5	0.9	10,34,36
Jute	51-84	12-20	5-13	0.2	36,37
Kapok	13.16	-	-	-	38
Kenaf	44-57	21	15-19	2	9,27,28
Phormium	67	30	11	-	16
Pineapple	80-81	16-19	4.6-12	2-3	9
Ramie	68-76	13-15	0.6-1	1.9-2	36
Sisal	43-78	10-13	4-12	0.8-2	9,25,33,39
Wood	45-50	23-30	27	2-2.5	9

Table 3: Physical properties of the plant fibres

Fibre type	Diameter (μm)	Length (mm)	Aspect ratio (l/d)	Micro-fibril angle (θ)	Bulk Density (kg/m^3)	Moisture regain (%)	[Source]
Abaca	17.0-21.4	4.6-5.2	257	-	1500	14.00	22
Bagasse	20	1.7	-	-	550-1250	-	9,10,22
Banana	-	2-3.8	-	11-12	1300-1350	-	9,10,22
Bamboo	10-40	2.7	-	-	1500	-	9,10,22
Coir	16.2-19.5	0.9-1.2	64	39-49	1250	13.00	10,22
Cotton	11.5-17	20-64	2752	20-30	1550	8.50	22,33
Flax	17.8-21.6	27.4-36.1	1258	5	1400-1500	12.00	22,41
Hemp	17.0-22.8	8.3-14.1	549	6.2	1400-1500	12.00	22,40,42,43
Jute	15.9-20.7	1.9-3.2	157	8.1	1300-1500	17.00	22,36,37
Kapok	15-35	Aug-32	724	-	384	10.90	22,38
Kenaf	17.7-21.9	2.0-2.7	119	-	1220-1400	17.00	22
Phormium	15.4-16.4	5.0-5.7	337	-	-	-	16,22
Pineapple	20-80	-	-	6-14	1520-1560	-	22,41,44
Ramie	28.1-35.0	60-250	4639		1550	8.50	22,41
Sisal	18.3-23.7	1.8-3.1	115	10-22	1300-1500	14.00	22,45

Physical Properties of Plant Fibres

Fruit fibres, leaf fibres and bast fibres are usually separated as bundles of fibres. The exact number of ultimate fibres in one bundle is not known because it is not possible to model the separation processes to produce a specific bundle diameter. Where authors have tried to quantify the number of ultimate fibres per bundle they do not describe the methods. However, the length of fibre ultimates of leaf fibres is between 2 - 60 mm [22]. Ramie, which is a bast fibre, can have ultimate fibres of up to 250 mm in length (Table 2). Some species of cotton fibre such as the Sea Island type are up to 74 mm long. Apart from ramie fibre, therefore, any fibre length quoted above 74 mm would be that of a fibre bundle. Robson *et al* [8] report fibre bundle length of between 60 - 100 mm implying that within the length of a bundle there will be several ultimate fibres joined end to end and side by side by natural binding materials such as lignin, wax and pectineous materials. Figure 1 (a) and (b) show cross-sectional and longitudinal views respectively, of hemp fibre, whereas Fig. 2 (a) and (b) show cross-sectional and longitudinal views respectively of sisal fibre. Fig. 2 (b) shows the spiral annular vessels in sisal, which are the nutrient pathways for the sisal leaf.

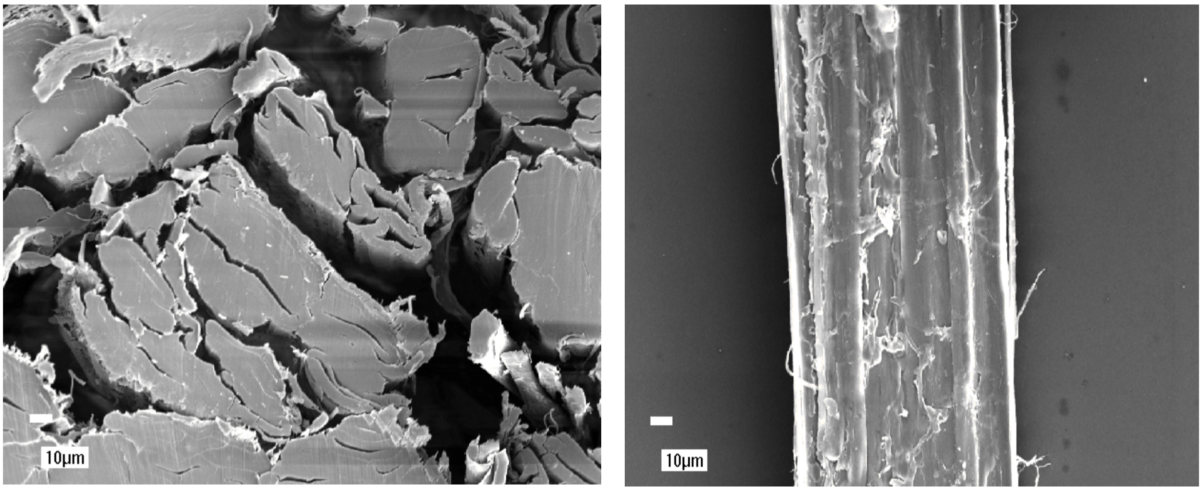

Figure 1: (a) Cross-sectional and (b) longitudinal views of hemp fibre

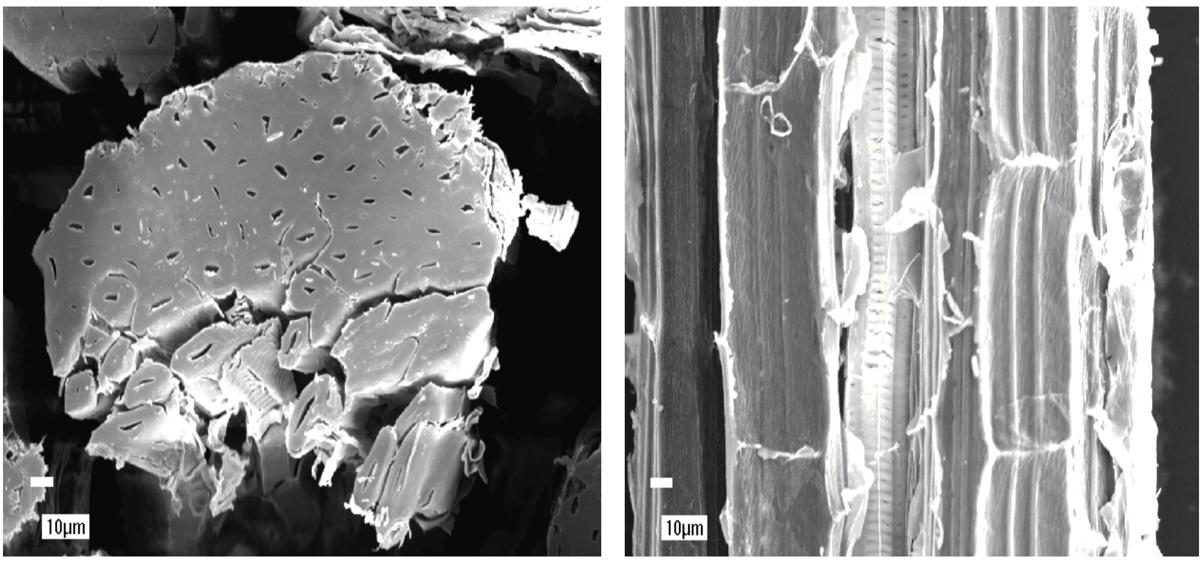

Figure 2: (a) cross-section and (b) longitudinal section through sisal fibre [30]

Coir is the reddish-brown fibrous mass and the average length of the ultimate fibres is about 1 mm (Table 3). The edges of some of the fibres have a distinct wavy outline and they are spindle-shaped lying along the fibre axis. The round stegmata to be found in the ash are particularly characteristic [22]. The fibre bundle can have between 30 - 300 or more ultimate fibres in its cross-section.

The physical characteristics of cotton fibre are the most interesting. It has layer arrangements, as is the case with all plant fibres, but its unique helical fibril winding formation distinguishes it from other fibres. The winding formation of the fibril along the major axis tends to have an alternate reversal direction as it winds along the fibre axis [5, 34]. The lumen of a mature cotton fibre is filled with protoplasm [47].

Kapok fibres are unicellular smooth, cylindrical and very lustrous. They are found in the pod of the kapok fruit and grow in the inner wall of the pod and sometimes on the seed. The fibres are coated with a highly water-resistant waxy cutin. It has a thin wall with an air filled lumen. The kapok fibre is lustrous and extremely light. When viewed through its cross-section, kapok fibres shows a wide air-filled lumen with a wall thickness of about 1- 2 µm. For instance, the apparent specific gravity of the Indian kapok fibre is about 0.0554 while that of Japanese kapok is about 0.0388. It is also reported that kapok fibre is six times lighter than cotton. It is buoyant, water repellent and slippery in nature [32]. If kapok fibre is compressed, it can support, on water, a mass, which exceeds its own mass by as much as twenty times and over. Kapok, after submerging will loose its buoyancy capacity very slowly.

Mechanical Properties of Plant Fibres

The fibre cell wall consists of the outer layer, which is the primary wall and the cuticle; the secondary wall consists of three layers S_1, S_2, and S_3, which connect the secondary wall to the lumen (Fig. 3). The S_1 is next to the primary layer and is known to be resistant to swelling media such as water and acetic acid just like the primary wall [47, 48]. The fibrillar structure layout in this layer is nearly perpendicular to the fibre axis and stabilises the fibre to lateral forces.

The S_2 layer, which constitutes the bulk of the secondary wall, swells easily breaking into fibrils, which follow a helical path and the fibrils are inclined at an angle to the fibres axis and dominates properties in tension [30, 47]. In cotton the fibrils in the S_3 layer are inclined more transversely to the fibre axis than are the fibrils in the S_2 layer and tend to resist the hydrostatic pressure exerted in the lumen.

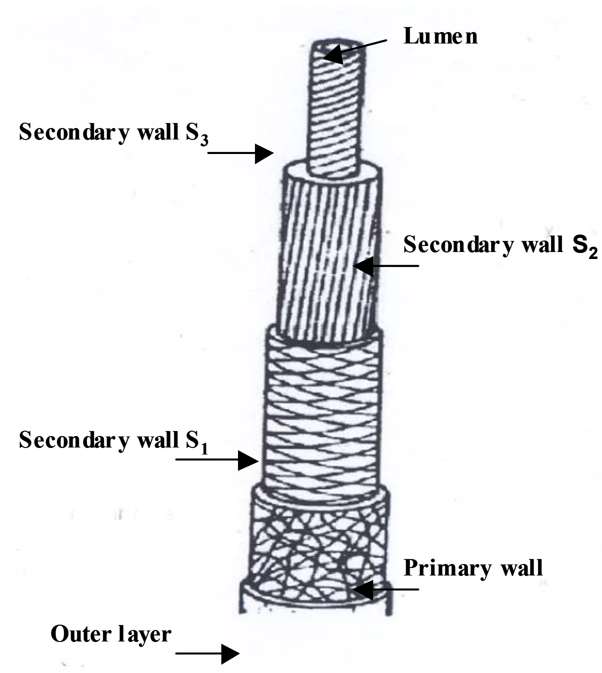

Figure 3: A simplified schematic structure of the single cell wall showing orientation of microfibrils in each of the major wall layers

It is worth mentioning that fibrous materials are commonly subjected to the following deformations: tension, compression, bending, torsion, shear, abrasion, wear and flexing [21] whilst in the plant source or in use. Our main concern is the performance of plant fibres in end use applications such as composites for industrial application.

Physical properties such as morphology, regularity or irregularity along and across the fibre main axis, crystalline packing order, amorphous content, and chemical composition all have an effect on the mechanical properties of fibres. In fact plant fibres are composites in nature with cellulose microfibrils as the reinforcement in a matrix of lignin and hemicellulose. The determination of mechanical properties (Table 4 and 5) can be predicted by using the rule of mixtures (ROM). For instance, equation (1) is used to estimate the stiffness or modulus of elasticity of the plant fibre cell wall [48, 49, 50, 51] along the fibre axis.

$$E_f = V_c E_c Cos^2\theta + V_{nc} E_{nc}$$

E_f is the effective modulus of the fibre, E_c, and E_{nc} are the elastic moduli of the crystalline and non-crystalline regions, and V_c and V_{nc} are the volume fractions of crystalline and non-crystalline regions and θ is the microfibril angle. The relationship between the stiffness (Young's modulus) and the microfibril angle is given in Fig. 4.

Figure 4 shows the decrease in the stiffness as the microfibril angle is increased. Fibres with lower microfibril angle have the highest stiffness. Pineapple fibre appears to deviate from the rule of mixtures theory, which leads to a suggestion that further work, is needed on the study of the fine structure of the pineapple fibre. Plant fibres can also develop defects during harvesting and subsequent processes such as scutching, and kinks can be formed during the needle punching in the mat forming process (Fig 5).

Figure 5 (a) shows nodes or defects along the hemp fibre while Fig. 5 (b) shows a severe defect caused by processing machines. Such natural and man-made defects are some of the major drawbacks in the optimisation of plant fibre mechanical properties. Similar defects can be seen in all plant fibres. Hughes [43] has also reported these observations.

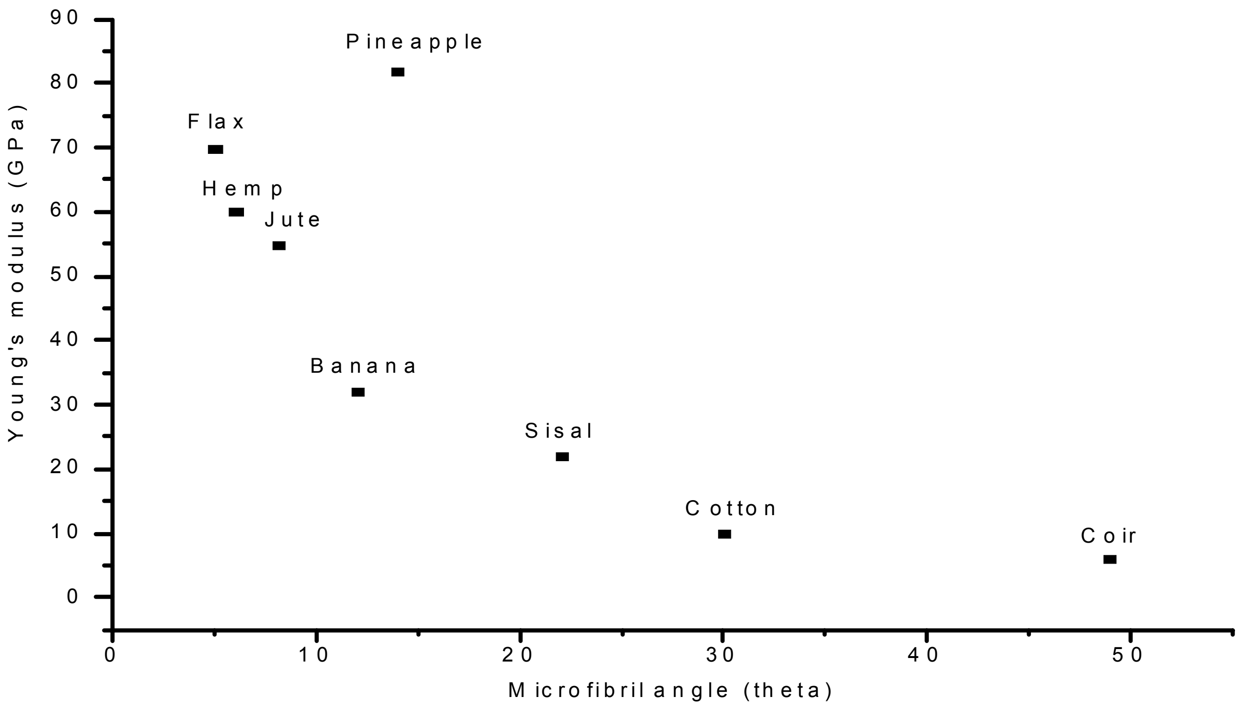

Figure 4: The relationship between the changes in the Young's modulus with respect to the plant fibre microfibril angle

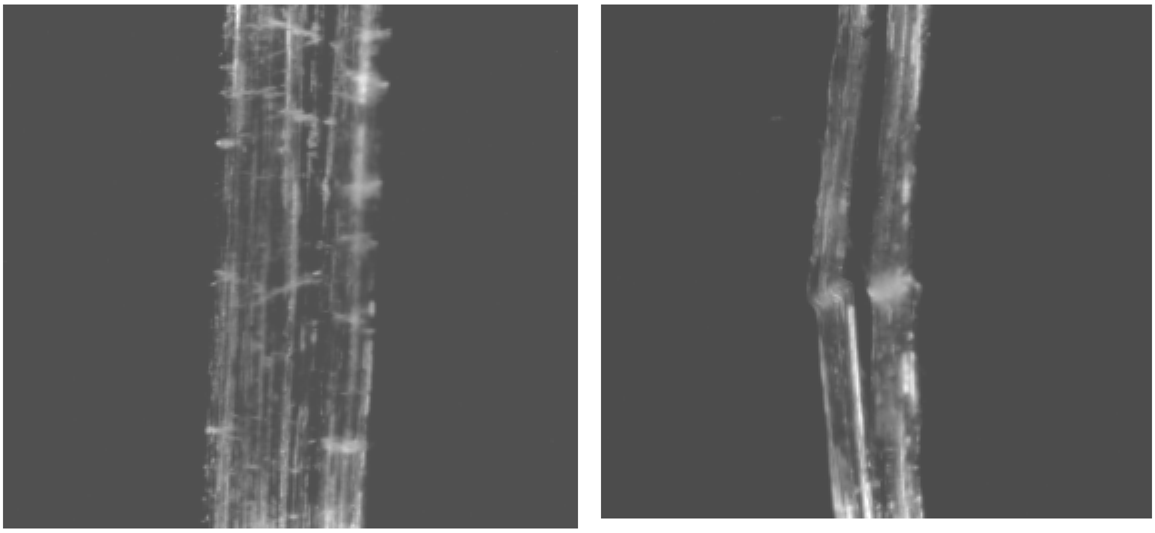

Figure 5: Hemp fibre (a) natural disjoints, (b) kinks acquired during processing such as carding (scale: 40X).

Table 4 shows mechanical properties of leaf and bast fibres and Table 5 shows mechanical properties of coir and seed fibres. Table 4 shows that pineapple fibre exhibits the highest specific strength and specific modulus followed by flax fibre and hemp fibre respectively. This implies that the weight of pineapple, flax and hemp fibres will be more suitable in composite manufacture due to the savings on weight economies over the rest of the fibres. More importantly, the same fibres exhibit high stiffness which means that they can be used as replacement for glass, carbon and high performance synthetic fibres such as Kevlar fibres in end uses where requirements for extreme stiffness is not a prerequisite. Similar argument can be expressed for composites in which the single cell fibres shown in Table 5 are used.

Applications of the Plant Fibres

Almost all the fibres have similar conventional end uses categorised in three groups namely apparel, household and industrial. Apparel applications are dresses or clothing where cotton fibre dominates the market, followed by flax, hemp and to certain extent kapok when in blends with cotton fibre. Household applications are curtains, upholstery, mattresses, quilts, coir and almost all seed, leaf and bast fibres are used in this category except bamboo fibre. Except kapok fibre all the fibres are used as industrial materials and the most common of these end uses are rope, shoes, sacks, carpets, fishing nets, paper and paper-felts.

Table 4: Mechanical properties leaf and bast fibres

Properties	Tensile strength (MPa)	Specific tensile strength (MPa)	Young's modulus (GPa)	Specific Young's modulus (GPa)	Failure strain (%)	[Source]
Abaca	12	-	41	-	3.4	7
Banana	529-914	392-677	27-32	20-24	1-3	7,23
Pineapple	413-1627	287-1130	60-82	42-57	0-1.6	38
Sisal	80-840	55-580	9-22	6-15	2-14	45
Bamboo	575	383	27	18	-	22
Flax	500-900	345-620	50-70	34-48	1.3-3.3	7
Hemp	310-750	210-510	30-60	20-41	2-4	40
Jute	200-450	140-320	20-55	14-39	2-3	40,43
Kenaf	295-1191	-	22-60	-	-	23
Ramie	915	590	23	15	3.7	22

Table 5: Mechanical properties of coir and the seed fibres

Fibres	Tensile strength (MPa)	Specific strength (MPa)	Young's Modulus (GPa)	Specific Young's modulus (GPa)	Failure strain (%)	[Source]
Coir	106-175	92-152	6	5.2	15-40	23
Cotton	300-700	194-452	6-10	4-6.5	6-8	30
Kapok	93.3	300	4	12.9	1.2	52

Table 6: Plant fibres reinforced composites

Composite	Fibre volume fraction (%)	Tensile strength (MPa)	Tensile modulus (MPa)	Flexural modulus (MPa)	Flexural strength (MPa)	Impact strength (kJ/m2)	[Source]
Sisal/polyester	50	47.1	12900	9370	80.43	-	57
Sisal/CNSL	50	24.5	8810	16150	-	-	15,54
Sisal/epoxy	40	37	3500	15930	266.5	-	58
Kapok-cotton fabric/CNSL	51	33.79	488.7	225.5	18.94	87.8	59
Kapok-cotton fabric/polyester	49	43.14	801.7	507	42.38	100.5	60

In the last 20 years there has been tremendous interest in the use of natural fibres as reinforcement for polymeric materials [44, 53, 54, 55]. This has been stimulated by the environmental cost of manufacturing energy-intensive, synthetic fibres such as glass, carbon and Kevlar. Two well established products are Tufnol 6F/45 which is an epoxy-cotton composite and the Tespa which is a phenol-wood fibre composite [56]. However, the poor strength properties of these two materials necessitated the need for further product optimisation. At the same time many claims have been made that on a weight-for-weight basis, the performance of the best plant fibre reinforced composites is comparable with that of conventional glass-epoxy compositions. Thermosetting polymer matrix and plant fibre composites find applications as electrical insulators (Tufnol 6F/45), semi-structural applications, and wear parts. BASF AG produces lignotoc, which is a sisal-polypropylene composite [56]. The building industry is another prospective end user of these plant fibre reinforced composites. Table 6 shows mechanical properties of some plant fibre reinforced composites.

Table 6 shows that sisal-cashew nut shell liquid (CNSL) composites offers the highest flexural stiffness compared to the rest and that kapok-cotton fabric reinforced CNSL exhibits fairly good impact properties. Both bending and impact are preferred property characteristics in the building and automotive industries.

Johnson Controls Interiors GmbH produces plant fibre reinforced thermoplastics for interior parts of cars [61, 62] and prototype truck boards are produced from banana fibre reinforced composites [21]. Sanad *et al.* [63] reports of successes in producing kenaf-polypropylene composites, which compares favourably with the glass-polypropylene and mica-polypropylene composites. It is also worth noting that cellulosics are increasingly being used as source of biomass fuel for the production of energy for domestic and industrial applications [64, 65, 66].

CONCLUSIONS

The recent environmental concern on the use of fossil-based fibres has resulted in the intensive research in property characteristics of plant fibres with the view of replacing the energy intensive synthetic fibres particularly in the composite manufacture. Plant fibres have the advantage over fossil-based fibres due to the low density and high specific stiffness, low cost and renewable. Plant fibres are also known to be carbon neutral thus environmentally friendly. Lower specific density of the cellulose-based fibres leads to weight savings in composite manufacture with direct advantages on transportation. The higher fibre volume fractions of plant fibres compared to those of the fossil fuel based reinforcements will result in significant material cost savings as plant fibres are cheaper than the matrices. However, research on property optimisation must continue to compete with the well-established glass and carbon reinforcements. With the substantial cuts in the expenditure in defence and aerospace programmes, some multinational companies are re-orienting their product range from high cost and high performance composites towards more environmentally friendly, less energy-intensive and lower cost plant fibre reinforced composites.

REFERENCES

[1] Farnfield, C. A., *Textile terms and definitions*, 7th (edn.), The Textile Institute, 1975.

[2] British Textile Technology Group (BTTG), 'Natural fibre types', 2001, http://www.textile.org.uk/Glossary/fibre_types.htm.

[3] Railey, K., 'The amazing hemp plant (Cannabis satavi L.)', H&B Online &content, 1993-2001 Chet Day, 2001, htt://chetday.com/hemp.html.

[4] Mikuriya, T.H., 'Marijuana: Medical papers', *in Medi-Comp Press*, Oakland, California, 1973, pp xiii-xxvii.

[5] Ashby, M.F., *Materials Selection in Mechanical Design*, 2nd Edn, Butterworth Heinemann, Oxford, (1992), p. 1.

[6] Anon, 'Commodity and trade division', *Food and Agriculture Organisation of the United Nations*, Economic and Social Department (ES), 2001, http://www.fao.org/.

[7] Bolton, A. J., *Mat. Tech.*, **9**, 1994, 12-20.

[8] Robson, D., Hague, J., Newman, G., Jeronimidis, G., and Ansell, M. P., 'Survey of natural materials for use in structural composites as reinforcement and matrices, Natural materials for composites, EC/4316/92', The Biocomposites Centre, University of Wales, Bangor, 1993, 1-71.

[9] Rowell, R.M. and Han, J.S. (2000): Characterisation and factors effecting fibre properties, Natural Polymers and Agrofibres Composites, Frolini, E, Leao, AL and Mattosso, L.H.C. (eds), San Carlos, Brazil, 115-127..

[10] Kozlowski, R. (2000): Potential and diversified uses of green fibres, 3rd International Wood and Natural Fibres Composites Symposium, 19th -20th September, 2000, Kassel, German, 1-14.

[11] Hunter, R.W. (1998): Will nonwoods become an important fibre resource for North America, World Wood Summit, 31st August -2nd September, 1998, Chicago, Illinois

[12] Riccio, F.A. and Orchard, L.P. (1999): Nonwood fibre resources: availability, infrastructure and feasibility. In Fifth International Conference on Woodfibre-Plastic Composites, Forest Products Society, Madison, Wisconsin, May 26-27, 1999, ISBN 0-892529-07-6.

[13] Smeder, B. and Liljedahl, S. (1996): Market oriented identification of important properties in developing flax fibres for technical uses, *Industrial Crops and products*, **5**, 149-162.

[14] Karus, M. and Kaup, M. (2002): Use of natural fibres in the Germany automotive industry, http://www.commonlink.com/~olsen/hemp/IHA/

[15] Mwaikambo, L.Y., Ansell, M.P. and Kawiche, G.M.: Development of natural fibre composites: An overview, workshop on "Materials selection and design", International Centre for Science and High Technology, Trieste, Italy, 15th-19th November, 1999.

[16] Carr, D.J., Cruthers, N.M., Laing, R.M. and Niven, B.E. (2005): Fibres from three cultivars of NewZealand and flax (Phormium tenax), Textile Research Journal, http://www.findarticles.com.

[17] Vincent, J. F., *Applied Composite. Materials*,7 (5-7), 2000, 331.

[18] Yyock, J.Y., Lombin, G. and Owonubi, J.J., in *Crop Science and Production in Warm Climate,* McMillan Publishers Limited, London, 1998.

[19] Van Sumare, C., Retting of flax with special reference to enzyme-retting. In: The Biology and Processing of Flax, Sharma, H. and Van Sumare, C. (eds), M Publications, Belfast, Northern Ireland, 1992, 157-198.

[20] Quinion, M., 'Fibres from the earth', *in World Wide Words*, 1996, http://www.quinion.com/words/articles/fibres.htm.

[21] Jarman, C. G. and Jayasundera, D. S., 'The extraction and processing of coconut fibre'. TPI, *in Ministry of Overseas Developmet*, London, 1975, pp. 25.

[22] Perry, D. R. (conv.), *Identification of textile materials*, The Textile Institute, Manara Printing Services, London, 1975.

[23] Abdul Khalil, H. P. S., 'Acetylated plant fibre reinforced composites', PhD Thesis, School of Agricultural and Forest Sciences, University of Wales, Bangor, Gwynedd, United Kingdom, 1999.

[24] Al-Qureshi, H. A., The use of banana fibre reinforced composites for the development of a truck body*, in 2nd International wood and natural fibre composites symposium*, Kassel, Germany, June 28-29, 1999, 32-1-32-7.

[25] Kirby, R. H. *Vegetable Fibres*, Interscience Publishers, New York, 1963, Chapter xvi.

[26] Sharma, H. S. S., (1987): Studies on chemical and enzyme retting of flax on a semi-industrial scale and analysis of the effluents for their physico-chemical components*,* International Biodeterioration, **3**(6), 329-342.

[27] Rowell, RM and Stout, HP (1998): Jute and kenaf, in *Handbook of Fibre Chemistry*, 2nd Edition, Lewis, M and Pearce, EM (eds), Marcel Dekker, New York, 465-504.

[28] Anon, 'Kenaf- an alternative fibre crop', *in Natural Life Magazine*, International Kenaf Association, 2001, 42.

[29] Bailey, T. L. W., Trip, V. W. and Moore, A. T., *Fibre Structure*, J. W. S. Hearle and R. H. Peters (ed.), Butterworths, London, 1963, p. 422.

[30] Morton, W. E. and Hearle, J. W. S., *PhysicalProperties of Textile Fibres*, The Textile Institute, Heinemann, London, 1975, pp. 1.

[31] Baker, HG *The evolution of the cultivated kapok tree: a probable West African product in ecological economic development in tropical Africa*, D. Berkeley (ed.), Brokensha, 1965, p. 185.

[32] Purseglove, J.W. (1987): *Tropical Crops Dicotyledon*, Vol. 1 and *2* combined, Longman Group, London, 1987, p. 33.

[33] El-Saied, H., Waly, A.I. and Basta, A.H. (2000): High water absorbents from lignocelluloses.I. Effect of reaction variables on the water absorbency of polymerised lignocelluloses, *Polymer Plastics and Technology Engineering*, **39**(5), 905-926.

[34] Joseph, S., Sreekala, M.S., Oommen, Z., P., Koshy, K. and Thomas, S. (2002): A comparison of the mechanical properties of phenol formaldehyde composites reinforced with banana fibres and glass fibres, *Composite Science and Technology*, **62**, p. 1857-1868.

[35] Jafferjee Brothers, Composite applications using coir fibres in Sri Lanka, Final Report, Project Number CFC/FIGHF/18 FT, Delf University of Technology, The Netherlands, 2003, 3-37.

[36] Sikorski, J. (1963): The fine structure os animal and man-made fibres, Fibre structure, Hearle J.W.S. and Peters, R.H. (Eds), Butterworth & Company and The Textile Institute, London, 269-310.

[37] Gassan, J., Chate, A. and Bledzki, A.K. (2001) Calculation of elastic properties of natural fibres, *Journal of Material Science*, **36**(15), 3715-3720.

[38] Mwaikambo, LY (2002): in *'Plant-based Resources for Sustainable Composites'*, PhD Thesis, University of Bath, Department of Engineering and Applied Science, Bath, 2002.

[39] Rowell, R.M., Sanadi, A.R., Caulfiel, DF and Jacobson, R.E. (1997): Utilisation of natural fibres in plastic composites, problems and opportunities. *in 'Lignocellulosic-Plastic Composites'*, 1997, Eds, Leao, AL, Carvalho, FX and Frollini.

[40] Mwaikambo, LY and Ansell, M.P: Mechanical properties of alkali treated plant fibres and their potential as reinforcement materials. Part I. Hemp fibre, (accepted for publication in *Journal of Materials Science*, June 3, 2005).

[41] Biogiotti J., Puglia, D. and Kenny, J.M., A review on natural fibres based composites-Part 1: Structure processing and properties of vegetable fibres, *Journal of Natural Fibres*, **1**(2), 2004, 37-68.

[42] Preston, R.D. (1963): Observed structure in plant fibres, Fibre structure, Hearle J.W.S. and Peters, R.H. (Eds), Butterworth & Company and The Textile Institute, London, 235-268.

[43] Hughes, J. M., 'On the mechanical properties of bast fibres reinforced thermosetting polymer matrix composites', PhD Thesis, School of Agricultural and Forest Sciences, University of Wales, Bangor, Gwynedd, United Kingdom, 2000.

[44] Chand, N, Tiwary, RK and Rohatgi, PK (1998): Bibliography, resource structure properties of natural cellulosic fibres-an annotated bibliography, *Journal of Materials Science*, **23**, 381-387.

[45] Mwaikambo, LY and Ansell, M.P: Mechanical properties of alkali treated plant fibres and their potential as reinforcement materials. Part II. Sisal fibre, (accepted for publication in *Journal of Materials Science*, July 13, 2005).

[46] Bodig, J and Jayne, BA (1982): *Characteristics Of Wood Composites, Mechanics Of Wood and Wood Composites*, Van Norstrand Reinhold Company Inc., New York, 1-47.

[47] Shenouda, D. J., *Applied Fibre Science*, 3, F. Happey, (ed.), Academic press, London, 1979, p. 127.

[48] Moncrieff, R. W., *Man made fibres*, Newnes-Butterworth, London, 1975, pp. 232.

[49] Hearle, J. W. S., Grosberg, P. and Backer, S., *Structural Mechanics of fibres, yarns and fabrics*, 1969, Chapter 4.

[50] Bodig, J. and Jayne, B. A., *Mechanics of wood and wood composites*, Van Nostrand Reinhold Company, 1982. p. 1.

[51] McLaughlin, E. C. and Tait, R. H. (1980): 'Fracture mechanism of plant fibres', *Journal of Materials Science*, **15**, 89 - 95.

[52] Mwaikambo, L.Y. , in 'Kapok fibre reinforced composites' MSc Thesis, University of Dar es Salaam, Department of Mechanical Engineering, Dar es Salaam, 1997.

[53] Roe, P. J. and Ansell, M. P. (1985), 'Jute reinforced polyester composites', *Journal of Materials Science*, **20**, 4015 - 4020.

[54] Bisanda, E. T. N. and Ansell, M. P., 'Properties of sisal - CNSL composites', *J. M. Sci* **27**, 1992, 1690 – 1700.

[55] White, N. M. and Ansell, M. P. (1985), *Journal of Materials Science*, **18**, 1549 – 1556.

[56] Gupta, T. N., 'Composite materials using local resources'*, in 'New and Advanced Materials Emerging Technologies Series'*, **3**, 1996, 3-29.

[57] Bisanda, ETN (1991): *Sisal Fibre Reinforced Composites*, Ph.D. Thesis, University of Bath, United Kingdom.

[58] Bisanda, E.T.N. and Ansell, M.P. (1991): The effect of silane treatment on the mechanical and physical properties of sisal-epoxy composites, *Comp. Sci. and Tech*., **41**(2), 163-176.

[59] Mwaikambo, L.Y. and Bisanda, E.T.N. (1999): The performance of cotton/kapok fabric-polyester composites, *Polymer Testing*, **18**(3), 181–198.

[60] Mwaikambo, L.Y., Tucker, N., Martuscelli, E., Avella, M. (2002): Kapok/cotton fabric-Cashew nut shell liquid composites, Sustainable Natural and Polymeric Composites–Science and Technology*, in 'Proceedings of the 23rd Risø International Symposium on Materials Science*', 2nd-5th Sept. 2002, Roskilde, Denmark, ISBN 87-550-3091-2, pp. 261-272.

[61] Beckmann, A., 'Anforderungen an Naturfasern aus der Sicht eines Kfz-Zulieferes für Innenraumteile', *in 'Proceedings of the '2nd International wood and natural fibre composites symposium'*, Kassel, Germany, 1999, 32-1-32-7.

[62] Maguno, A. (1999): Vegetable fibres in automotive interior components, *in 'Proceedings of the '2nd International Wood and Natural FibreComposites Symposium'*, Kassel, Germany, 1999, 32-1-32-7.

[63] Sanadi, A. R., Caulfield, D. F., Jacobson, R. E. and Rowell, R. M. 'Renewable Agricultural fibres as reinforcing fillers in plastics: mechanical properties of kenaf fibre-polypropylene composites', *in I & E Research*, 1995, 1889-1896.

[64] Reed, A. and Williams, P.T. (2003): Thermal processing of biomass natural fibre wastes by pyrolysis, *International Journal of Energy Research*, **28**(2), 131-145.

[65] Puglia, D., Biagiotti, J. and Kenny, J.M., A review of natural fibres-based composites, Part II: Application of natural reinforcements in Composite materials for automotive industry, **1**(3), 2004, 23-65

[66] Kenny, J.M., Natural fibre composites in the European automotive industry' *in 'Proceedings of the Sixth International Conference on Woodfibre-Plastic Composites*', Forest Products Society, Madson, Wisconsin, 15th-16th May, 2001, pp. 9-12