

# Composite Materials from Natural Resources: Recent Trends and Future Potentials

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## 1. Introduction

Composites are combinations of two or more than two materials in which one of the materials, is reinforcing phase (fibres, sheets or particles) and the other is matrix phase (polymer, metal or ceramic). Composite materials are usually classified by type of reinforcement such as polymer composites, cement and metal- matrix composites (Chemical and Materials Engineering Department, home Page 2011; About.com, home page, 2011). Polymer matrix composites are mostly commercially produced composites in which resin is used as matrix with different reinforcing materials. Polymer (resin) is classified in two types thermoplastics (polyethylene (PE), polypropylene (PP), polyether ether ketone (PEEK), polyvinyl chloride (PVC), polystyrene (PS), polyolefin etc.) and thermosets (epoxy, polyester, and phenol-formaldehyde resin, etc.) which reinforces different type of fibre like natural (plant, animal, mineral) and man-made fibre for different application. In metal matrix composites, metal is one of important part of element and other part may be metal, ceramic or organic compounds. Cement matrix composites are made up of cement and with aggregate and basically used in building applications.

Due to increase in population, natural resources are being exploited substantially as an alternative to synthetic materials. Due to this, the utilization of natural fibres for the reinforcement of the composites has received increasing attention. Natural fibres have many remarkable advantages over synthetic fibres. Nowadays, various types of natural fibres (Taj et al., 2007) have been investigated for use in composites including flax, hemp, jute straw, wood, rice husk, wheat, barley, oats, rye, cane (sugar and bamboo), grass, reeds, kenaf, ramie, oil palm, sisal, coir, water hyacinth, pennywort, kapok, paper mulberry, banana fibre, pineapple leaf fibre and papyrus. Natural fibres are largely divided into three categories depending on their origin: Mineral based, Plant based, and Animal based. In general, a mineral based composite is asbestos and is only a naturally occurring mineral fibre (silicate based mineral). In 2006, 2.3 million tones of asbestos were mined worldwide. Russia was the largest producer with about 40.2% world share followed by China (19.9%), Kazakhstan

(13.0%), Canada (10.3%), and Brazil (9.9%) (Wikipedia, home page, 2010). The main properties of asbestos fibres are their thermal, electrical, and sound insulation; inflammability; matrix reinforcement (cement, plastic, and resins), adsorption capacity, wear and friction properties (friction materials), brake linings and chemical inertness (except in acids). Asbestos fibres are often mixed with cement or woven into fabric or mats/ sheets (Britannica home page, 2011; Wright, 2005).

Plant-based natural fibres are ligno-cellulosic in nature composed of cellulose, hemicellulose, and lignin, whereas animal based fibres are of proteins, e.g., silk and wool. Natural fibre-reinforced polymer composites have attracted more and more research interests owing to their potential as an alternative for synthetic fibre composites such as glass or carbon fibre composites (Bledzki & Gassan, 1999). Natural fibre composites possess the advantages such as easy availability, renewability of raw materials, low cost, light weight and high specific strength, and stiffness. It is expected that in the near future biodegradable polymers will replace synthetic polymers, at least in some specific applications where a short life of the product will be more desirable. Natural polymers are considered suitable to replace synthetic ones in some specific applications where a long span life is not required. Natural fibre thermoplastic composites are relatively new family of composite materials. In such composites, a natural fibre/filler (such as kenaf fibre, wood fibre, hemp, sisal etc.) is mixed with a thermoplastic (e.g., polyethylene, polypropylene, PVC etc.) to produce the composite. In the last few years, thermoplastics as well as thermoset-based natural fibre composites (NFCs) have experienced a tremendous growth in the auto industry due to environmentally friendliness, renewability of these fibres, good sound abatement capability, and improved fuel efficiency resulted from the reduced weight of the components. These composite materials have received much commercial success in the semi-structural as well as structural applications. For example, interior parts such as door trim panels from natural fibre polypropylene (PP) and exterior parts such as engine and transmission covers from natural fibre-polyester resins are already in use in auto industry. Advantages of thermoplastic NFC over thermoset-based NFC include the greater design freedom as they are suitable for injection molding and extrusion processing in addition to the recycling possibilities.

## 2. Classification of natural fibres

Natural fibres are classified into three categories. These are plant fibres, animal fibres and mineral fibres (Fig. 2.1) (FAO home page, 2010). Plant fibres are important types of natural fibres and these are generally comprised mainly of cellulose, hemicellulose, lignin, pectin. Prominent natural fibers are cotton, jute, flax, ramie, sisal and hemp. Cellulose fibres are mainly used in manufacturing of paper and cloth. This fibre is categorized into seed fibres, leaf fibres, bast fibre/ stem fibre, fruit fibre, stalk fibre (Table 2.1 and Fig. 2.1.1).

### 2.1 Animal fibre and their sources

Animal fibres generally comprise proteins. Examples are wool, silk, human hair and feathers etc. Wool has several qualities that distinguish it from hair or fur; it is crimped, it is elastic, and it grows in staples (D'Arcy, 1986). Fibre taken from animals or hairy mammals e.g. sheep wool, goat hair (cashmere, mohair), alpaca hair, horse hair etc. Wool is the textile fibre.

**Silk fibre:** Silk is a natural protein fibre, some forms of which can be woven into textiles. The best-known type of silk is obtained from the cocoons of the larvae of the mulberry silkworm. The shimmering appearance of silk is due to the triangular prism-like structure of the silk fibre, which allows silk cloth to refract incoming light at different angles, thus producing different colours.

**Human hair:** The human body, apart from its skin, is covered by follicles which produce thick terminal and fine hair. Hair is a filamentous biomaterial that grows from follicles found in the dermis. Most common interest in hair is focused on hair growth, hair types and hair care but hair is also an important biomaterial primarily composed of protein, notably keratin. Hair is a non homogenous complex material which can be associated with a polymer. It is made up 95% of Keratin.

**Feathers:** Feathers are among the most complex integumentary structure found in vertebrates and are formed in tiny follicles in the epidermis, or outer skin layer, that produce keratin proteins (Schor & Krimm, 1961; Linus Pauling & Robert, 1951; Hornik et al., 2005). Feathers are one of the epidermal growths that form the distinctive outer covering or plumage on birds. They are considered the most complex integumentary structures found in vertebrates, (Prum & Brush, 2002, 2003; Pettingill, 1970). Fig 2.1.2 shows different species of feathers.

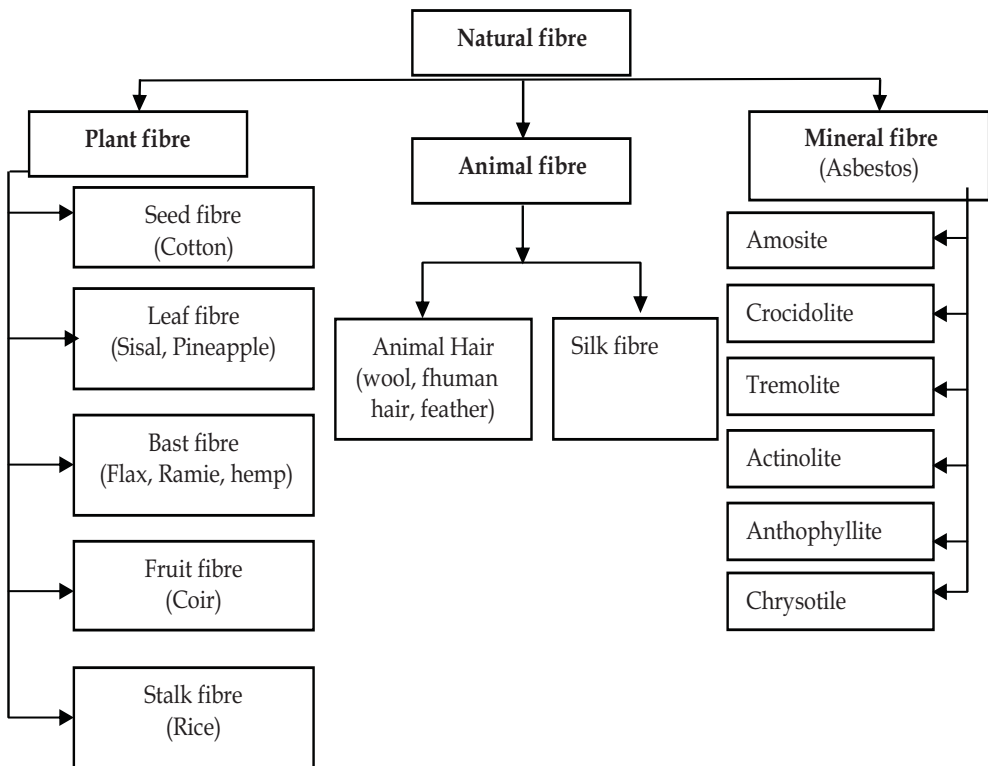


Fig. 2.1 Classification of natural fibre

| S. No. | Category                       | Plant fibre   |
|--------|--------------------------------|---|
| 1.     | <b>Bast fibre / stem fibre</b> | <b>Jute fibre:</b> Generally jute fibres are extracted from the ribbon of the stem. It is used as packaging material (bags), carpet backing, ropes, and yarns (Fig 2.1.1a) and in many other decorative items.  |
| 2.     | <b>Leaf fibre</b>              | <b>Sisal:</b> Sisal plant belongs to the agave family (Agavaceae). The plant looks like giant pineapples. The soft tissue is scraped from the fibres by manually or machine (Fig 2.1.1b). It is mainly used for mats, carpets and many other reinforcement materials.   |
| 3.     | <b>Seed fibre</b>              | <b>Hemp:</b> Hemp fibres have long been valued for their high strength and long fibre length, and have been used extensively in the fabrication of ropes and sails, as well as for paper and textiles. Hemp is a hardy plant, and grows well in a moderately cool climate. Hemp fibres are mainly composed of cellulose, hemicellulose, and lignin and pectin (Fig 2.1.1c). |
|        |                                | <b>Ramie:</b> Ramie is an expensive and durable fibre. The ramie plant can easily grow in fabrics. It is widely used in making of furniture covers and wall paper etc.  |
|        |                                | <b>Cotton:</b> Cotton is the most important fibre used in the textile industry. Cotton is generally collected by picking which is generally carried out by hand. Comparison with other natural fibres, cotton is mainly used in the manufacturing of clothes, blankets, carpets (Fig 2.1.1d).   |
|        |                                | <b>Flax:</b> Flax fibre one of the strongest fibre among natural fibre. Flax has good heat conducting properties. However, constant creasing in the same place in sharp folds tends to break the fibre. Flax is used for the production of linen, canvas, ropes and sacks.  |
| 4.     | <b>Fruit fibres</b>            | <b>Coir:</b> Generally coconut fibres (Fig 2.1.1e) are obtained from the husk of the fruit of the coconut palm. These coconut fibres are strong, light and easily withstand heat and salt water.  |
| 5.     | <b>Stalk fibre</b>             | These fibres are actually extracted from the stalks of the plant. For example, rice, barley, straws of wheat, bamboo and grass.   |

Table 2.1 Plant fibre and their sources

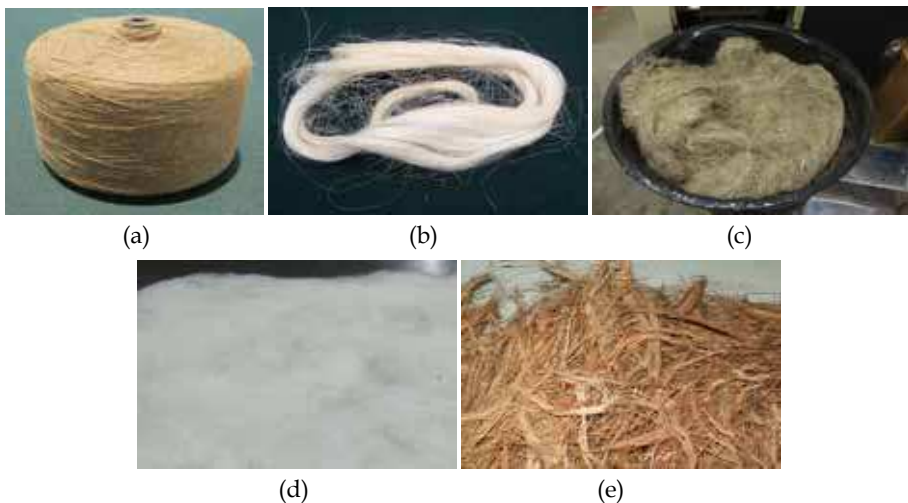


Fig. 2.1.1 (a) Jute yarn (b) Sisal fibre (c) Hemp fibre (d) Cotton fibre (e) Coir fibre

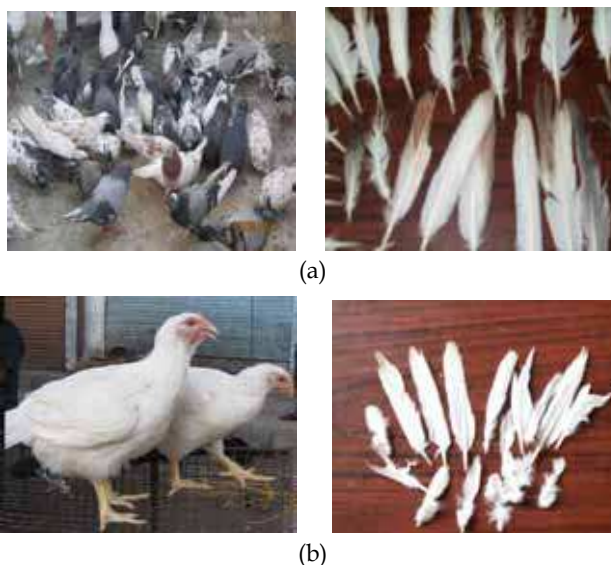


Fig. 2.1.2 Feathers picture of different species (a) Bird feather, (b) Chicken feather

## 2.2 Mineral fibres and their sources

Mineral fibres are mainly naturally occurring fibre or slightly modified fibre processed from minerals, can be defined into the following forms. Asbestos is the group of minerals that occur naturally in the environment as bundles of fibres. These fibres are resistant to heat, fire and bad conductor of electricity. Asbestos mineral are silicate compound, contain silicon and oxygen in their molecular structure. Asbestos minerals are divided into two major group's serpentine asbestos and amphibole asbestos (ATSDR home page, 2011). Asbestos is mainly divided into six fibrous minerals. The six types include (1) Amosite asbestos, (2) crocidolite asbestos, (3) tremolite asbestos, (4) actinolite asbestos (5) anthophyllite asbestos and chrysotile asbestos.

Amosite asbestos is the second most prevalent type of asbestos found in building materials. It is also known as brown asbestos and sometimes "grey" asbestos. Its colour comes from the natural presence of magnesium and iron. Generally amosite was used as a fire retardant in thermal insulation product (Maacenter, home page, 2011). Crocidolite also known as blue asbestos was the least used in commercial products (Britannica home page, 2011). Generally tremolite forms by metamorphism of sediments rich in dolomite and quartz. Mainly pure magnesium tremolite is creamy white in colour, but due to the increasing iron content colour grades to dark green. At high temperature it is toxic and converts to diopside (Mesorfa, home page, 2011). Another type is actinolite is derived from the Greek word aktis, meaning beam or ray. Actinolite is normally found in metamorphic rocks like cooled intrusive igneous rocks, aureoles. Anthophyllite also known as amphibole mineral occurs of metamorphism of magnesium-rich rocks and dolomite shales. It is an amphibole mineral. Chrysotile asbestos also known as white asbestos. It is a very soft, fibrous silicate mineral of phyllosilicates. It is the most widely used forms of a member of serpentine asbestos family. This fibre is long, hollow cylinders and very strong.

### 3. Extraction and processing of plant fibre

#### 3.1 Jute fibre

Retting is the process of extracting fibre from the long lasting life stem or bast or the bast fibre plants. The retting process of jute fibre can be classified as: mechanical retting (hamming), chemical retting (boiling & applying chemicals), steam/vapor/dew retting and water or microbial retting. Availability of water and the cost of retting process is main parameter to select type of retting. To extract fine fibres from jute plant, first observation were require that if the fibre can easily be removed from the jute hurd or core, then the crop is ready for harvesting. Jute stalks after harvesting are submerged in soft running water in bundles for 20 days, and is grabbed in bundles and hit with a long wooden hammer to make the fibre loose from the jute hurd or core. Afterwards, the extracted fibres is further washed with fresh water and allowed to dry. Finally, obtain dry processed fibre for different application.

#### 3.2 Sisal fibre

Sisal fibre can be extracted from its leaves by Retting, Boiling and Mechanical extraction methods. Water retting is a traditional biodegradation process involving microbial decomposition (breaking of the chemical bonds) of sisal leaves, which separates the fiber from the pith. The fibers are washed and processed further. This process takes 15-21 days for a single cycle of extraction and degrades the quality of fiber. Retting is a very slow, water intensive process, unhygienic, and not eco-friendly. Fiber extracted by this method is poor in quality. Boiling is another extraction method, in which leaves of sisal plant are boiled, subsequently beating is done then after washing and sun drying we may get the usable clean fiber. This method is not suitable for large-scale extraction. Mechanical extraction involves inserting leaves into a machine "raspador machine "and pulling the raw material out (Fig 3.2.1). This process does not deteriorate fiber quality and is suitable for small-scale operations and is efficient, versatile, cost effective and eco-friendly process. Residues produced during and after extraction of fiber are about 96% which is useful for biogas



Fig. 3.2.1 Mechanical process of sisal fibre extraction using raspador machine

generation, composting, and isolation of a steroid, ecogenin, making paper, biodegradable polymer and wax.

### 3.3 Flax fibre

Flax fibres were collected from diverse sources with the intention to provide characteristically different physical and chemical properties. The fibre bundles are located just under the skin and embedded in bast tissue. Harvested the plants are spread over the ground for retting, in which the pectin layer that binds the fibres to the bast tissue and the flax stem is broken down. In past, retting (water retting) was usually performed by immersing bundles of flax stem into running water or in standing water in ponds. Fermentation by anaerobic bacteria degrades the pectins and other substances that bind the fibres to the stem. After the fibres have been loosened from the stem, the stem is broken on a roller; afterwards these broken stem parts fibres are removed. The total process to remove the wooden stem from the fibres is also called decortications. These fibre bundles are still relatively coarse and thick which are then processed in the hackling process for further application.

### 3.4 Cotton fibre

Fifteen percent of world cotton production is ginned on roller gins and almost all the rest of cotton is seeing ginned in most countries. Cotton is a shrubby plant belongs to Mallow family. Its name refers to the cream-colored fluffy fibers surrounding small cotton seeds called a boll. The small, sticky seeds are separated from the wool in order to process the cotton for spinning and weaving. De-seeded cotton is cleaned, carded (fibers aligned), spun, and woven into a fabric that is also referred to as cotton. The harvested cotton is cleaned to separate dirt, seeds, and short lint from the cotton. At the gin, the cotton enters module feeders that fluff up the cotton before cleaning. Some gins use vacuum pipes to send fibers to cleaning equipment where trash is removed. After cleaning, cotton is sent to gin stands where revolving circular saws pull the fiber through wire ribs, thus separating seeds from the fibre (Madehow, home page, 2010).

## 4. Processing of animal fibre

### 4.1 Wool

Wool is considered to be a protein called keratin. Its length usually ranges from 2 to 35 centimetres depending on the breed of sheep. Each piece is made of three essential components; the cuticle, the cortex, and the medulla. The cuticle is the outer layer. The cortex is the inner structure made up of millions of cigar-shaped cortical cells. In wool processing, wool straight off a sheep contains a high level of grease which contains valuable lanolin, as well as dirt, dead skins and vegetable matter. This semi grease wool can be worked into yarn and knitted into particularly water-resistant sweaters. Processing of wool is shown in following Fig. 4.1.1.

The major steps to process wool from the sheep to the fabric are shearing, cleaning and scouring, grading, sorting, carding, spinning, weaving and finishing. In wool shearing process, sheep are sheared once a year-usually in the springtime. The fleece recovered from a sheep can weigh between 2.7 and 8.1 kilograms. While most sheep are still sheared by hand, now a days many new techniques have been developed for this (Table 4.1).

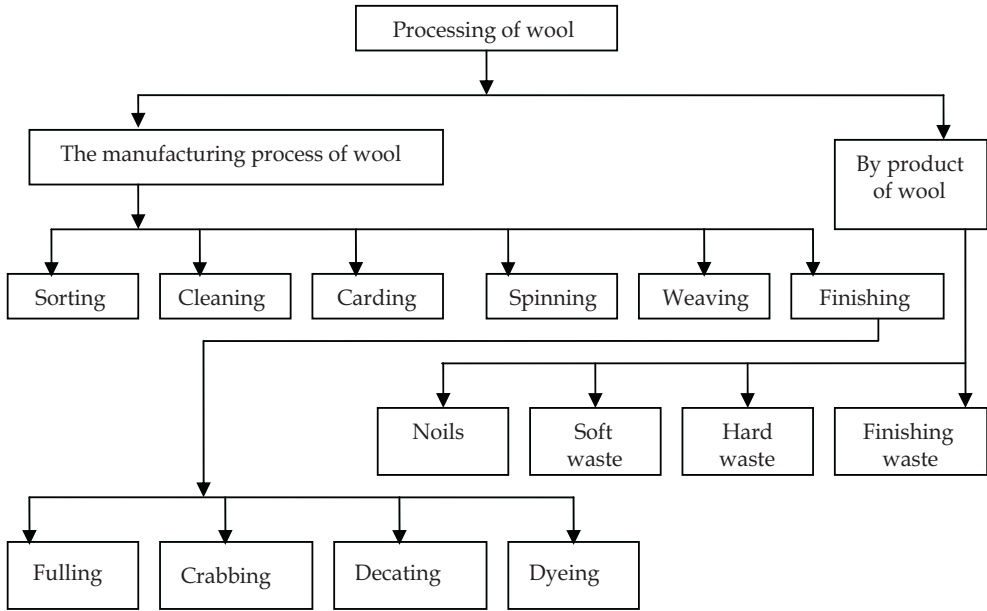


Fig. 4.1.1 Wool processing

|    |           |   |
|----|-----------|---|
| 1. | Sorting   | In the process of sorting, the wool is broken up into sections of different quality fibres. The best quality of wool comes from the shoulders and sides of the sheep which is used for clothing.  |
| 2. | Cleaning  | Raw wool contains dirt, grease and sand. To remove these contaminants, the wool is scoured in a series of alkaline baths containing soap, water and soda ash.   |
| 3. | Carding   | In the process of wool carding the wool fibres are passed through a series of metal teeth. Carding also removes residual dirt and other matter left in the fibres. Carded wool intended for worsted yarn. Carded wool to be used for woollen yarn is sent directly for spinning.  |
| 4. | Spinning  | Thread is formed by spinning in wool spinning process. The fibres together to form one strand yarn. Spinning for woollen yarn is typically done on a mule spinning machine. When yarn is spun, it is wrapped around bobbins and cones.  |
| 5. | Weaving   | The next step is wool weaving. In this process the wool yarn is woven into fabric usually manufacturers use two basic weaves for weaving; the plain weave and the twill. Plain weave used for the woollen yarns which are made into fabric. Worsted yarn can create fine fabric with delicate patterns using a twill weave. So the results are more smooth fabric and more tightly woven. |
| 6. | Finishing | After the process of weaving both worsted and woollens undergo a series of finishing procedure such as: Fulling (immersing the fabric in water to make the fibres interlock), Crabbing (permanently setting the interlock), Decating (shrink- proofing), Dyeing.  |

Source: Madehow, home page, (2011)

Table 4.1 Wool processing



## 4.2 Silk

Making of silk is different from that of other natural fibres. There are many steps involved in silk manufacturing as shown in Fig. 4.2.1.

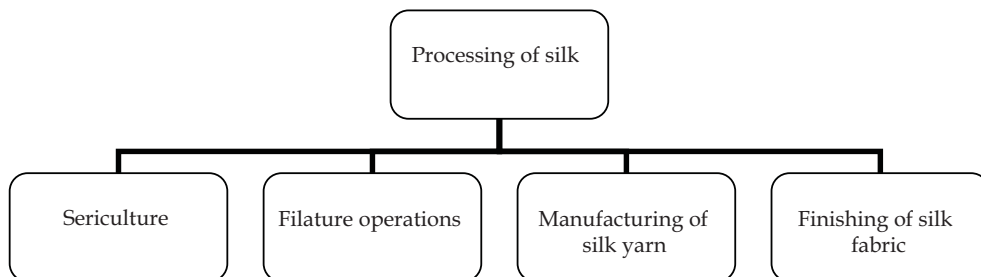


Fig. 4.2.1 Silk processing

### Sericulture

The major steps of silk processing are sericulture in which cultivation of cocoons has been done for their filaments. Raw silk is obtained from the species of moth called *Bombyx mori*. The female moth lays around 355 to 405 eggs and the moth die soon after. Larva of about 3 mm is hatched from the eggs. They are carefully nurtured and are fed five times a day on chopped mulberry leaves. After transforming into caterpillar, they are ready to spin cocoon for which racks, clusters of twigs or straw are provided. This caterpillar have small openings this is known as spinnerets through which they secrete a substance like protein. This substance when it comes in contact with air solidifies and the filament thus formed a spun around the silk worm. In three days the cocoon gets completed which is about a peanut shell size. The filament is held together by sericin or silk yarn.

### Filature operations

The raw silk is unwound from cocoons in the factories known as filature and the process known as filature operations. Here the cocoons are sorted based on their colour, size, texture and shape. After that immersed in hot and cold water to soften the sericin. In this process whole seracin is not removed as it protects the delicate filament in further operations.

### Silk yarn manufacturing

The next process is "reeling" (unwinding the filament from the cocoon). This reeled silk is formed into silky yarn or silk thread through the process called 'throwing.' The raw silk skeins are sorted according to their physical properties like colour, length quantity, and size and washed in warm water with soap for softening the seracin. After drying, placed in reel from where the silk is wound on bobbins. During winding, the silk strands are given desired amount of twist. To get equal diameter throughout the length, the yarn is run through rollers. Following kinds of silk yarns are obtained: Thrown singles (Three to eight silk filaments are twisted together in only one direction, Tram (a slight twist is given to two to four untwisted singles), Crepe (individual raw silk filaments are twisted together), and Organize (a raw-silk thread, usually used as a warp thread).

### Finishing of silk fabric

Calendering (a finishing process), cireing and singeing (a process applied to yarns and fabrics to produce an even surface) finishing process are applied to different silk fabric in

order to improve their appearance, durability and to make them smooth and with fine texture. Processing and lustering removes wrinkles from the finished fabric. One finish that is unique to silk fabric is 'weighting.' The weight of silk is lost during the process of degumming. Weighting is done during the dyeing process. This weighted silk is less compactly woven when compared to the unweighted silk. This weighting gives it crispness, and luster (Teonline, home page, 2011).

### **4.3 Human hair**

#### **Washing**

In the process of washing hairs, fibres were bleached using a solution of hydrogen peroxide (7 %) in the presence of respective surfactants. pH 10 of bleaching solution was adjusted with NH<sub>4</sub>OH and the treatment was carried out for 1 hour at 60 °C. The tress was then rinsed with 2 % aqueous acetic acid solution and then with demineralised water until pH was neutral. The excess water was removed by placing the tress onto a paper towel. The tress was dried up under ambient temperature in open air (20± 2 °C).

#### **4.4 Feather**

Processing of feather start by scrapping the inner part of feathers quill. Then start cutting the feather from the bottom to the top at the centre. After that remove the excess from the front and back. Then put the feather into the feather holder. Sand the quill with 36 grit paper to thin it out after; make sure the other side is thin sand the quill for final processing (Legionnaire Archery, home page, 2011).

## **5. Processing of mineral fibres**

Asbestos is found in the nature, due to natural weathering of rocks, mining. Asbestos fibres are released into the environment through erosion and carried by the wind. Magnetic sensor (magnometer) is used to locate the deposition of asbestos in earth crust. After asbestos is removed from the crust, it is processed and divided into groups according to fibre length. Longer fibres are separated out for weaving into a cloth-like material.

### **5.1 Mining**

Asbestos fibres are separated from the rocky ore using physical methods because chemical composition of ore is similar to the fiber, so chemical methods are not used. Mining process is first step used in processing of asbestos fiber from ore. Most asbestos mining operations are conducted in an open-pit mine and branch drilling technique. Open pit type mining is a surface mining method; it is used for those asbestos containing ore which lies near the surface of ore.

### **5.2 Milling**

The second main step after mining is milling of ore using different series of crushing machine with vacuum and vibrating plate. In milling process two type of milling are used (i) dry and (ii) wet milling operations. Wet ore is collected from bottom of stock pile (where ore is store after mining) and dry ore present in upper part of mine ore. The dry ore is goes to rotating cylinder dryer and then different crushing was done to fine the ore size. Using

vacuum aspiration vibrating screen, under aerodynamic nature of asbestos fibre readily collects in the vacuum area. Rock circuit is used for separating fiber according to length of fiber and then fiber is compressing and packaged in bags (Madehow, home page, 2011; Virta, 2002). Asbestos processing is shown in Fig 5.2.1.

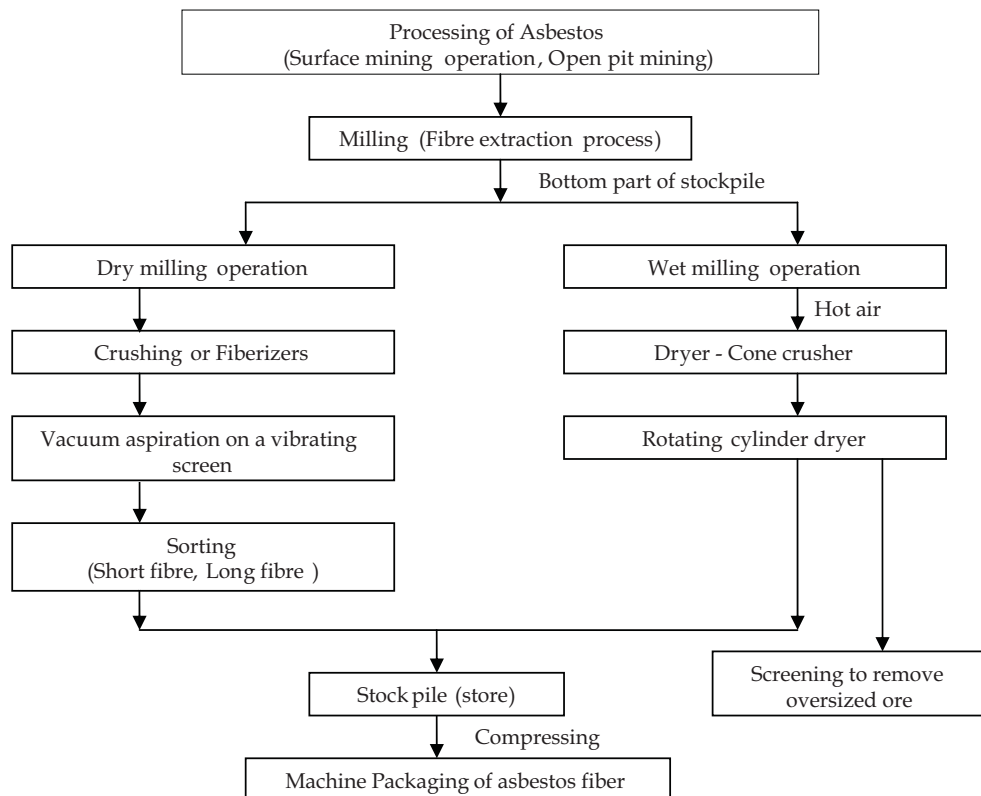


Fig. 5.2.1 Flow chart of asbestos processing

## 6. Properties of natural fibre

### 6.1 Characteristics of plant fibre

Plant fibres are a composite material designed by nature. The fibres are basically a rigid, crystalline cellulose micro fibril-reinforced amorphous lignin and/or with hemicellulosic matrix. Most plant fibres are composed of cellulose, hemicellulose, lignin, waxes, and some water-soluble compounds. The percentage composition of each of these components varies for different fibres. Generally, the fibre contains 60-80 % cellulose, 5-20% lignin and up to 20 % moisture (Taj et al., 2007; Wang et al., 2008). During the biological synthesis of plant cell walls, polysaccharides such as cellulose and hemicellulose are produced simultaneously. Lignin fills the space between the polysaccharide fibres, cementing them together. This lignification process causes a stiffening of cell walls and the carbohydrate is protected from chemical and physical damage (Taj et al., 2007). The chemical composition of natural fibres

varies depending upon the type of fibres. The chemical composition as well as the structure of the plant fibres is fairly complicated. Hemicellulose is responsible for the biodegradation, micro absorption and thermal degradation of the fibre as it shows least resistance, whereas lignin is thermally stable but prone to UV degradation. The details of different plant fibre such as sisal, flax, cotton and jute fibre are discussed as follows.

Sisal fibre varies in their quality. The large variations in its chemical compositions are because of its different sources, age, extraction methods, etc. (Chand, 1988). As reported by Wilson, (1971) sisal fibre contains 78% cellulose, 8% lignin, 10% hemicelluloses, 2% waxes, and about 1% ash by weight, whereas Rowell et al., (1992) reported that sisal contains 43-56% cellulose, 7-9% lignin, 21-24% pentosan, and 0.6-1.1% ash. The work carried out by Chand and Hashmi (1993) showed that the cellulose and lignin contents in sisal vary from 49.62 to 60.95% and 3.75 to 4.40%, respectively. According to Mohanty et al., (2005) sisal fibre contain 66-78% cellulose, 10-14% hemicellulose, 10-1% lignin, 10% pectin, 10-22% moisture content, and 2% waxes (Mohanty, 2005). It is apparent from the above studies that chemical composition and other characteristics of sisal fiber depends on various agro-climatic conditions under which sisal is grown, age of the sisal plant and extraction process (Saxena et al., 2011).

Flax fibres bundles are isolated from the plant by breaking and scutching processes. The isolated fibres are composed of a few fibres, bonded together by a relatively weak pectin and lignin interphase, which is at some places along the fibres virtually absent. The fibres are composed of elementary fibres of diameters around 15 mm and lengths between 20 and 50 mm. The fibre consists of about 10-40 elementary fibres in cross section. The elementary fibres are bound together by a pectin interphase. This interphase is much stronger than the interphase between the technical fibres (Oever, 2000). Flax fibre contain 71% Cellulose, 18.6-20.6 % Hemicelluloses, 2.2% Lignin, 2.3% Pectin, 8-12 Moisture Content, 1.7% Waxes and 5-10° Microfi brillar Angle (Taj et al., 2007; Saxena et al., 2011). Cotton fibre contains 85-90% Cellulose, 5.7% Hemicelluloses, 0-1 % Pectin, 7. 85- 8.5 moisture Content, 0.6 % Waxes (Taj et al., 2007; Saxena et al., 2011). Jute fibre contain 61.1-71.5 % Cellulose, 13.6-20.4% Hemicelluloses, 12-13% Lignin, 0.2% Pectin, 12.5-13.7 Moisture Content, 0.5% Waxes and 8°Microfi brillar Angle (Taj et al., 2007; Saxena et al., 2011).

| <b>Fibre</b> | <b>Density<br/>(g/cm<sup>3</sup>)</b> | <b>Tensile<br/>strength<br/>(MPa)</b> | <b>Elongation<br/>at Break (%)</b> | <b>Tensile<br/>Modulus<br/>(GPa)</b> | <b>Reference</b>                               |
|--------------|---------------------------------------|---------------------------------------|------------------------------------|--------------------------------------|--|
| Jute         | 1.3                                   | 393-773                               | 7.0 - 8.0                          | 5.5-12.6                             | Taj et al., (2007)                             |
|              | 1.3 - 1.46                            | 345 - 1500                            |                                    | 2.7 - 3.2                            | Baiardo et al., (2004)                         |
| Flax         | 1.29                                  | 663                                   | 5.0                                | 160                                  | "  |
|              | 1.5                                   | 345-1035                              | 2.7-3.2                            | 27.6                                 | Taj et al., (2007)                             |
|              | 1.4-1.5                               | 600-1100                              | 1.5-2.4                            | 45-100                               | Saxena et al., (2011)                          |
| Cotton       | 1.5-1.6                               | 287-597                               | 7.0-8.0                            | 5.5-12.6                             | "  |
|              | 1.5                                   | 200- 40                               | 6-7                                | 8.0                                  | Saxena et al., (2011)                          |
| Sisal        | 1.45                                  | 468 - 640                             | 3-7                                | 9.4 - 22                             | Lamy & Pomel, (2002);<br>Saxena et al., (2011) |
|              | 1.35                                  | 550 ± 100                             | 24 ± 0.4                           | 4±0.6                                | Baiardo et al., (2004)                         |

Table 6.1.1 Physical and Mechanical properties of different plants fibre

### **Engineering properties of plant fibre**

The mechanical properties and physical properties of natural fibres vary considerably depending on the chemical and structural composition, fibre type and growth conditions. Mechanical structure of plant fibres is much lower when compared to those of the most widely used competing reinforcing glass fibres. However, because of their low density, the specific properties (property-to-density ratio), strength, and stiffness of plant fibres are comparable to the values of glass fibres (Taj et al., 2007; Saxena et al., 2011). Table 6.1.1 shows some of the engineering properties of natural fibre.

## **6.2 Characteristics of animal fibre**

### **Physicochemical properties of wool fibre**

Wool fibres have a low tenacity which have excellent elongation and elastic recovery. Wool fabric is durable with moderate resistance. Wool is a poor conductor of heat. These fibres are more hygroscopic than any other fibre. They have excellent resiliency. Wool generally retains its shape fairly well during normal use. Wool garments required to be handled carefully when they are hand washed in order to avoid shrinkage. Wool fibre is very sensitive to some alkalis due to keratin which break down its disulfide linkages and weaken the fibre properties. At the burning, wool fibre burns slowly with a slight sputtering when a flame is presented. The residue from burning is brittle, black bead that crushes when squeezed. Generally, Wool fibres are fairly resistant to bacteria (Composite Fabrics, home page, 2010).

### **Physicochemical properties of silk**

Durability of silk fibre is very strong. Its strength is excellent in relation to its fineness. It may lose up to 20 percent of its strength in wet state. Silk has moderate abrasion resistance. Silk cannot return to its original shape even when it is stretched in a small amount, it remains slightly stretched. Therefore, fabrics made of cultivated silk have a smooth appearance and luxurious hand. Silk fibre is a poor conductor of heat just like wool, it is comfortably warm in the winter. Silk fibres do not shrink as the molecular chains in fibres are not distorted easily. Silk swells only a small amount when wet and it has moderate resistance to wrinkling. Silk have higher tensile strength than glass fibre or synthetic organic fibres, good elasticity, and excellent resilience. The chemical compositions are, in general, silk fibroin of 75–83%, sericin of 17–25%, waxes of about 1.5% and others of about 1.0% by weight. The densities of silk fibres are in the range of 1320–1400 kg/m<sup>3</sup> with sericin and 1300–1380 kg/m<sup>3</sup> without sericin (Sang & Donghwan, 2005). Silk is resistant to most mineral acids but will dissolve in sulfuric acid. It is resistant to dilute mineral acids and organic acids. Silk is resistant to attack by bacteria and fungi. Sunlight accelerates silk decomposition which is more susceptible to ultraviolet damage than wool (Neste & Shaker, 2001; Lewis, 1989; Wei et al., 2005).

### **Mechanical properties of Silk**

Silk is one of the strongest natural fibres but loses up to 20% of its strength when wet. It has a good moisture regain of 11%. Its elasticity is moderate to poor, if elongated even a small amount it remains stretched. It can be weakened if exposed to too much sunlight. Generally Silk fibres have a triangular cross section with rounded corners. This reflects light at many different angles, giving silk a natural shine. It has a smooth, soft texture that is not slippery,

unlike many synthetic fibres. Its denier is about 4.5 g/d when dry and 2.8-4.0 g/d when moist. The physico mechanical properties of wool and silk are as shown in Table 6.2.1.

| S. No | Properties                   | Wool    | Silk        | Reference                         |
|-------|------------------------------|---------|-------------|-----------------------------------|
| 1.    | Type                         | Natural | Natural     | Quazi et al., (2010)              |
| 2.    | Melting temperature (°C)     | 570-570 | -           | Matbase, (2010) home page, (2010) |
| 3.    | Service temperature (°C)     | 100-400 | -           | "                                 |
| 4.    | Density (Kg/m <sup>3</sup> ) | 1.3     | 1.3-1.38    | "                                 |
| 5.    | Tensile strength (MPa)       | 125-200 | 650-750     | "                                 |
| 6.    | Elongation (%)               | 20-40   | -           | "                                 |
| 7.    | Polarity                     | -       | Hygroscopic | Quazi et al., (2010)              |
| 8.    | Young's modulus (MPa)        | -       | 16          | "                                 |
| 9.    | Elongation at failure (%)    | -       | 18-20       | "                                 |
| 10.   | Crystallinity (%)            | -       | 65 -70      | "                                 |

Table 6.2.1 Physico-mechanical properties

### Physicochemical properties of human hair

Hair is surprisingly strong. Cortex keratin is responsible for this property and its long chains are compressed to form a regular structure (Valeria et al., 2009). The physical proprieties of hair involve, stretching, elasticity and hydrophilic power. Generally physical proprieties of hair depend on its geometry (Kolar & Miller, 1972; Juez & Gimier, 1983; Valeria et al., 2009). Due to elasticity, hair can resist forces that could change its shape, its volume or its length. Elasticity is one of the most important properties of hair. Hair fibre has an elastic characteristic and it may undergo moderate stretching. The elasticity of hair depends on the long keratin fibres in the cortex. Both natural sunlight and artificial ultraviolet light break down chemicals in the hair and damage its elasticity. The texture of hair depends mainly on average diameter of the individual hairs. There are different chemical components present in the human hair it is an "integrated" system. The different chemical components in human hair act together to maintain the normal flow of functions. The chemical composition of hair fibre includes essential functional elements like amino acids, keratin, melanin, and protein. Proteins are present also within the cuticle which provides elasticity to the hair. Hair, from its growth under the skin of the scalp, is filled with a fibrous protein called keratin. The keratin protein found in hair is called hard keratin. It is made up of eighteen amino acids. The lipid content of the hair is not constant but varies with age and other factors. In the hair structure, lipids are present in Inner Root Sheaths and hair shaft lipids provide sheen to the hair and contribute towards its tensile properties.

Melanin is the hair pigment which gives color to the skin and hair. The size, type and distribution of the melanosomes will determine the natural color of the hair (Hair dressing home page, 2011; Juez & Gimier, 1983). Amino acids are the principle building block of the keratin proteins found in hair fibres, and approximately 20 different amino acids are present in these proteins. The chemical composition of hair fibres is dominated by carbon, which comprises about 45% of the atomic structure of hair. Oxygen accounts for approximately 28%, nitrogen 15%, hydrogen 7%, and sulfur 5%. Several essential trace elements are also

present in hair fibres including iron (20 - 220 ppm), copper (10-20 ppm), zinc (190 ppm), and iodine (0.6 ppm) (Wella, 1999).

### **Mechanical properties of hair**

The mechanical properties of  $\alpha$ -keratin fibres such as hair fibres and wools are primarily related to the two components of the elongated cortical cells, the highly ordered intermediate filaments (microfibrils) which contain the  $\alpha$ -helices, and the matrix in which the intermediate filaments are embedded (Feughelman, 2002). Chemical treatment, bleaching and dyeing is known to be one of hair cuticle and cortex damage producing and properties impairing factors (Neste & Shaker, 2001; Lewis, 1989; Wei et al., 2005). Mechanical properties such as elasticity and durability are governed by the interactions of proteins in the cortex. The cortex is a complicated, disulfide cross-linked polymer system comprising the crystalline low-sulfur proteins and the globular matrix of high-sulfur proteins.

### **Physicochemical properties of feather**

The moisture content of processed feathers can vary depending upon processing and environmental conditions. The moisture content of feather fibre is an important variable that can have implications ranging from transportation costs to mechanical properties. Hong and Wool, (2005) reported a typical value of 8 mm for fibre length. Barone and Schmidt, (2005) measured the density of chicken feather fibre, obtained from feather fibre Corporation, by displacing a known volume and weight of ethanol with an equivalent amount of fibre. Density of solid keratin was studied by Arai et al., (1989) and also Barone and Schmidt, (2005) reported an apparent density of feathers and reported fibre lengths of 3.2-13 mm for the feather fibre. Hong and Wool (2005) have reported that the density of feather fibre is 0.8 g/cm<sup>3</sup>. However, Barone and Schmidt's (2005) reported a value of 0.89 g/cm<sup>3</sup> and is relatively similar to the value (0.80 g/cm<sup>3</sup>) cited by Hong and Wool (2005) when compared with a value of 1.3 g/cm<sup>3</sup> reported by keratin (Arai et al., 1989). Barone and Schmidt, (2005) reported fibre lengths of 3.2-13 mm. The structure of keratin, affects its chemical durability which is the primary constituent of feathers. Keratin shows good durability and resistance to degradation.

### **Mechanical properties of feather**

The first step in exploring the mechanics of feathers in birds was to investigate how variable the properties of keratins are between species. While examining the stiffness (Young's modulus) properties of a wide range of bird species, it has been found that there is a very little evidence of systematic differences in properties between species. Hence, the mechanical performance of feathers were therefore, controlled more by shape than by material properties. The fracture toughness of  $\beta$ -keratin has proved to be very high, around 10 kJm (Reading, home page, 2011). The mechanical properties of feather fibre are related to the structure of keratin. The mechanical properties of bird's feathers are highly related to their function (Bonser & Purslow, 1995). Further, work carried out by Cameron et al., (2003) confirmed that the mechanical properties of feather keratin vary appreciably along the length of the rachis. Using x-ray diffraction, Cameron et al., (2003) discovered that, moving from calamus to tip, the keratin molecules become more aligned than at the birds skin before returning to a state of higher disorder towards the rachis tip. George et al., (2003b) studied turkey feather fibre properties for fibres at different positions along the rachis. It was found that both the tenacity and modulus of turkey feather fibre, measured in g/denier,

increased with the distance from the calamus. Purslow and Vincent (1978) measured the elastic modulus of feather rachis from pigeons with and without inner quill. Dehydrated feather rachises were tested in bending. Taylor et al., (2004) studied the affect of moisture content on mechanical properties.

### 6.3 Characteristics of mineral fibre

Asbestos was formerly known as a 'miracle mineral' due to its special properties that include strength, flexibility, low electrical conductivity, and resistance to heat and chemicals. Asbestos does make construction better in many ways. It has been used for thousands of products in innumerable workplaces.

#### Physicochemical properties of asbestos fibre

Asbestos almost has become a superstar in the world of industrial chemistry due to its physical properties however manufacturing and utility of asbestos has been banned in many developing and developed countries. It has remarkable thermal stability, resistance for thermal and electrical and non-flammable. Asbestos fiber can be split up into fine fibres, and these fibers are enough strong and flexible material and are use for thermal and electrical insulator, flame retardant, chemically inert, insulating purpose. Asbestos fibres are odourless and tasteless. Asbestos group fibers are insoluble in water, air and soil. Its colour will depend on type, and metallic composition. Crocidolite is the most colourful elements, which have iron and sodium and its colour shades are lavender, blue and green. The colours of other type of asbestos are depending on amount of iron. Asbestos is divided into two major groups: amphiboles and serpentines. Both amphibole and serpentine asbestos are fibrous. The amphiboles group are double-chain silicates (inosilicates). The basic structural unit is  $(\text{Si}_4\text{O}_{11})^{6-}$  with side groups that are responsible for the overall amphibole structure. The quantity and positioning of metal atoms (sodium, calcium, manganese, magnesium, iron (II), iron (III) and aluminium) differentiate amphiboles from one another (Virta, 2002). The serpentine group of minerals have the formula  $\text{Mg}_3\text{Si}_2\text{O}_5(\text{OH})_4$ . Serpentine structure is a bending sheet. Chrysotile is very elastic. Asbestos is easily turned into a dust with finger pressure this properties called friability. Due to this nature asbestos fibres releases into the atmosphere and cause health problems (Virta, 2002; Burdetti, 2007).

#### Mechanical properties of asbestos fibre

The tensile strength of a single asbestos fibre, based on the strength of silicon oxygen bonds (Si-O-Si) in the silicate chain. Industrial fibres have lower tensile strength, because of the presence of different types of structural or chemical defects. For higher tensile strength measurements short and thin fibres have used. The tensile strengths of amosite and crocidolite are equivalent to that of chrysotile. Tensile strength is very much influenced by iron content in amphiboles, the since iron-oxygen bonds located in the fibre axes, are strong. Iron content of asbestos fibres effect the tensile strength this is as observed increasing trend tensile strength in the order amphiboles < tremolite< amosite < crocidolite. The tensile strength of asbestos fibres is change with temperature and sharply distinguishes chrysotile and amphiboles. In chrysotile when temperature is increased up to 500°C slightly increase in tensile strength is observed, which the beginning of due to dehydroxylation reaction is. In the case of amphiboles, when temperature increases more than 200°C decreases tensile strength is observed at 350°C Crocidolite has lost 50% of its initial tensile strength. Physical, chemical and mechanical properties of asbestos are shown in Table 6.3.1.



| Group      | Type                                 | Chemical formula  | Diameter<br>$\mu\text{m}$ | Specific<br>gravity | Tensile<br>strength<br>(MPa) | Reference   |
|------------|--------------------------------------|---|---------------------------|---------------------|------------------------------|---|
| Serpentine | Chrysotile<br>(white colour)         | $\text{Mg}_3(\text{Si}_2\text{O}_5)(\text{OH})_4$   | 0.1-1                     | 2.2-2.9             | 1100-<br>4400                | Wikipedia,<br>home page,<br>(2011);<br>Virta,<br>(2002)   |
| Amphibole  | Amosite/<br>Grunerite (Brown colour) | $\text{Fe}_7\text{Si}_8\text{O}_{22}(\text{OH})_2$  |                           | 3.4 -3.5            | 1500-<br>2600                | "   |
|            | Crocidolite/<br>Richterite (Blue)    | $\text{Na}_2\text{Fe}^{2+}_3\text{Fe}^{3+}_2\text{Si}_8\text{O}_{22}(\text{OH})_2$  | 0.1-2                     | 3.0-3.5             | 1400-<br>1600                | USEPA, home<br>page 2011;<br>CDCP, home<br>page, (2010);<br>Maacenter,<br>home page,<br>(2010);<br>Virta,<br>(2002) |
|            | Tremolite                            | $2\text{CaO}.5\text{MgO}.8\text{SiO}_2.$<br>$\text{H}_2\text{O}$  |                           | 2.9-3.2             | < 500                        | Virta, (2002)   |
|            | Anthophyllite<br>Actinolite.         | $7.\text{MgO}.2\text{SiO}_2.2\text{H}_2\text{O}$<br>$\text{Ca}_2(\text{Mg},\text{Fe})_5\text{Si}_8\text{O}_{22}(\text{OH})$ |                           |                     | 3.00                         | -<br>-  |

Table 6.3.1 Physical, chemical and mechanical properties of asbestos group

## 7. Composite fabrication

### 7.1 Plant fibre composite

There are several methods for making of natural fibre composites. Most of the techniques commonly used for making glass fibre composites are applicable for making natural fibre composites. However, the well known methods for composites making are as follows: Hand Lay-up/Spray up is one of the cheapest and most common processes for making fibre composite products. In this process, the mold is waxed and sprayed with gel coat and cured in a heated oven. In the spray up process, catalyzed resin is sprayed into the mold, with chopped fibre where secondary spray up layer imbeds the core between the laminates resulting a composite. In hand layup processing, both continuous fibre strand mat and fabrics are manually placed in the mold. Each ply is sprayed with catalyzed resin and with required pressure compact laminate is made. Resin transfer molding (RTM) provides high quality finished surface on both the sides of composites with a relatively low energy makes perfect shapes. The fabricator generally gel coats the mold halves, then lays continuous or chopped strand mat and closes the mold. Resin transfers into mold through injection pressure, vacuum pressure, or both. Cure temperature depends on the resin system. Compression molding is a molding technique for making composite materials with low unit cost with faster cycle times. Sheet molding compounds (SMC) is a sheet that sandwiches fibre between two layers of resin paste. Fibre/Fabric drop onto the paste and a second film carrier faces with another layer of resin. When the SMC is ready for molding, the mold is closed, clamped, and between 500 and 1,200 psi pressure is applied. After curing, mold is opened and the sheets were removed manually or through an injector system and ready for use.

Automated injection molding of thermoset bulk molding compound (BMC) has increasingly taken over markets previously held by thermoplastics for application in electrical and automotive components, housing appliances, and motor parts. BMC is a low-profile (nearly zero shrinkage) formulation of a thermoset resin mix with 15–20% chopped fibre. Injection molding is a fast, high volume, low pressure, and closed process. Injection speeds are typically 1–5 s and nearly 2,000 small parts can be produced per hour. A ram or screw type plunger forces a material shot through the machine's heated barrel and injects it into a closed, heated mold. Heat build-up is carefully controlled to minimize curing time. After cure and injection, parts need only minimal finishing. Filament winding is an automated, high volume process that is ideal for manufacturing pipe, tank, shafts and tubing, pressure vessels, and other cylindrical shapes. The winding machine pulls dry fibres from supply racks through a resin bath and winds the wet fibre around a mandrel. Pultrusion is the continuous, automated closed-molding process that is cost effective for high volume production of constant cross sectional parts. Pultruded custom profiles include standard shapes such as channels, angles, beams, rods, bars, tubing and sheets (Saxena et al., 2008).

### 7.2 Animal fibre composite: Fabrication of the wool fibre composites

As a composite, wool fibres have been combined with polyester fibres and spun into multistrand yarn as threads, again for use in garments. Traditionally, wool fibres have been spun into multilayer fibres in the form of threads, which are then knitted into cloth and utilized for the manufacture of garments. The composite matrix was prepared from polyester resin with 1% hardener (methyl ethyl ketone peroxide). Samples of composite sheets were prepared in the laboratory from skeins of wool laid alternatively with layers of resin mixture, and placed in a rectangular mould. The top of the mould was sealed and hydraulic pressure of 1.2 MPa was applied for a period of 24 h. The pressure was then reduced to 0.6 MPa, the sample sheet was removed and excess solid resin trimmed. The composite so obtained was cured in air. This process was repeated for sample sheets containing wool by mass of 40, 30, 20 and a control sheet of polyester resin. Fabrication of different types of silk fibre composites, human hair composites and feather fibre composites can be made with hand lay up technique and compression molding which has been already described in fabrication of plant fibre composites.

### 7.3 Mineral fibre composite

**The Hatschek process:** Mineral fiber composites are made through Hatschek and Magnani processes which are commonly used for making mineral fibre cement composites. The Hatschek process (or wet process) is the most widely used method of fabrication of asbestos composites. About 7-10% solids by weight of aqueous slurry of asbestos and cement matrix is used to a holding tank which has a number of rotating screen cylinders. The cylinders select solid matter removing some of the water. A continuous felt group travels over the surfaces of the cylinders and select a thin layer of formulation from each cylinder. The formulation is the gash up on a steel calendar, or incorporation roll, need of thickness of product. The material is now compressed by pressure rolls, which are direct contact with the assimilation rolls. For sheet manufacture, the layer built up on the assimilation roll is mechanically cut off and drops onto a conveyor to be transferred for curing. For making of corrugated roofing, the flat sheet is removed to a corrugating station and put on oiled steel moulds for shaping.

**The Magnani (or semi-dry) process:** The Magnani (or semi-dry) process is used to prepare corrugated sheet and pipes. In this process, thickness of material can be increased at the peaks and troughs of the corrugations sheet and hence the bending strength is greater. About 50% solids of the thick slurry materials of this process can flow equivalently and directly onto a felt conveyor which goes through numerous vacuum boxes to dewater the formulation. The corrugated roofing is compressed over a corrugated past by a shaped roller. Pipe formation is similar to the Mazza process. The formulation of the matrix, and hence the cure of the product, has varied from country to country and between companies within a country. The formulations remain confidential to the company or its licensees and only general details will be discussed here. The autoclaved curing process has always been favored in Australia and the USA and in some European countries. In the autoclave process, the matrix is usually a mixture of ordinary Portland cement (OPC) and finely ground sand (silica), or lime and silica. The product, after an initial pre-cure period in air, is cured in an autoclave in a steam environment say 8 hours at 170-180 °C. The cured sheets are virtually at full strength after autoclaving and can be dispatched from the factory in a short time. By contrast the more traditional air-cured products require 14-28 days of air curing before they can be dispatched involving considerable stock inventory. The air-curing process is lower in capital outlay as no high-pressure autoclaves and steam raising plant are required; however, cement is more expensive than silica, and therefore material costs are higher (Shah et al., 1981). Attempt were made at AMPRI-CSIR Bhopal to make asbestos substitute composites replacing asbestos fiber with sisal fiber, though hand lay-up method Fig 7.3.1 show corrugated sisal cement roofing sheets and plan sheet prepared at AMPRI, Bhopal using hand lay up technique.



Fig. 7.3.1 Sisal composites: (a) Sisal fiber cement roofing sheet (b) Sisal pulp cement composites panel

## 8. Properties of composite

### 8.1 Properties of plant fibre composites

Increased importance of renewable resources for raw materials and recyclability or biodegradability of the product at the end of the useful life is demanding a shift to natural fibers such as cotton, flax, kenaf, hemp, sisal etc in applications in addition to there exist technical advantages like strength, lightweight, and noise absorption etc.

### 8.1.1 Jute composite

Jute fibre possesses moderately high specific strength and stiffness which make it suitable for reinforcement in composite. Development of cheap high performance composite from jute has always been a major concern area due to the easy availability, low cost, high strength (tensile strength). Various composites were developed with different thermoplastic and thermo set polymers. Jute reinforced polyester, epoxy composite and jute reinforced polypropylene, polystyrene thermoplastic composite were developed from very long time and research were focused on its mechanical performance which is summarized here.

#### 8.1.1.1 Jute-polyester composite

Dynamic mechanical properties of jute composite were found to be very high. Dash et al., (1999) processed and analyzed the mechanical properties of jute reinforced polyester composite. Tensile and flexural properties were investigated in terms of bleached and control jute composite at various fibre loading. Composites mechanical properties such as tensile, flexural strain, toughness and moduli were compared and found that 60% fibre loading showed highest tensile strength (90.52±8.83). In between control and bleached jute polyester composite, control jute polyester composite (JPH(C)) showed highest tensile property whereas bleached jute polyester (JPH (B)) composite showed highest flexural strength as shown in table 8.1.1.1 (Dash et al., 1999). Jute polyester hot curing (Bleached) composites showed 18440MPa flexural modulus and 171MPa flexural strength whereas Jute polyester hot curing (Control) composites showed 140MPa flexural strength and 13850MPa flexural modulus (Dash et al., 1999). Composite made from bleached fibre showed higher flexural properties due to the increase in the extent of chemisorptions of bleached jute fibre surface (Dash et al., 1999).

| Composite                            | Fibre Volume (%) | Tensile Strength (MPa) | Ult Strain (%) | Tensile modulus (MPa) |
|--------------------------------------|------------------|------------------------|----------------|-----------------------|
| Jute Polyester Hot curing (Control)  | 60               | 132± 6.33              | 5.83± 0.68     | 2956± 774             |
| Jute Polyester Hot curing (Bleached) | 60               | 117± 21.32             | 6.687± 0.82    | 2106± 229             |
| Jute Polyester Hot Curing            | 55               | 78.15± 7.45            | 5.04± 0.72     | 2535± 884             |
| Jute Polyester Hot Curing            | 60               | 90.52± 8.83            | 3.82± 0.12     | 4189± 403             |
| Jute Polyester Hot Curing            | 66               | 80.6± 12.5             | 3.27 ± .40     | 4072± 402             |
| Jute Polyester Hot Curing            | 71               | 70.31± 6.89            | 2.85± 0.25     | 4328± 358             |

Source: Dash et al., (1999)

Table 8.1.1.1 Mechanical properties of jute polyester composite

#### 8.1.1.2 Jute vinyl ester composite

Ray et al. (2001) used a solution of NaOH (5%) to treat the jute fibre for 0, 2, 4, 6 and 8 hours at 30°C. For the vinyl ester resin composites reinforced by 35 wt% jute fibre treated for 4 h,

an improvement of 20% for the flexural strength, 23% for the flexural modulus and 19% for the laminar shear strength was observed (Ray et al., 2001). Results are summarized in Table 8.1.1.2.

| <b>% Fibre volume</b> | <b>Flexural Strength (MPa)</b> | <b>Flexural Modulus (GPa)</b> | <b>Breaking Energy (J)</b> |
|-----------------------|--------------------------------|-------------------------------|----------------------------|
| 0                     | 2.120                          | 2.951                         | 0.8227                     |
| 8                     | 106.30                         | 4.220                         | 0.2948                     |
| 15                    | 128.60                         | 5.544                         | 0.3399                     |
| 23                    | 145.70                         | 7.355                         | 0.3531                     |
| 30                    | 180.60                         | 10.030                        | 0.4799                     |
| 35                    | 199.10                         | 11.890                        | 0.5543                     |

Source: Ray et al., (2001)

Table 8.1.1.2 Flexural properties of jute vinyl ester composite

### 8.1.1.3 Jute epoxy composite

After Jute polyester analysis, Mishra et al., (2000) investigated the effect of 50 % fibre loading of (control and Bleached) jute fibre reinforced epoxy composite on mechanical performance and found that bleached composite showed better flexural and impact strength whereas controlled jute epoxy composite showed higher tensile strength at 50 % fibre loading which are summarized in Table 8.1.1.3 (Mishra et al., 2000). In bleaching, fibre delignified and dewaxed and cell separated with each other and surface becomes clean with increased micro roughness which enhances the fibre matrix mechanical interlocking. Gassan & Bledzki, (1997) also investigate the effect of coupling agent between fibre and matrix and observed enhancement in mechanical performance. Table 8.1.1.3 showed that tensile strength (131MPa) and tensile modulus (2.35GPa) of 50% fibre loaded bleached jute reinforced epoxy composite is lesser than the corresponding 148 MPa and 3.18GPa of unbleached jute epoxy composite. In contrary, flexural strength (155MPa) and flexural modulus (14.232GPa) of raw jute epoxy composite is lesser than the corresponding 196MPa and 20.4GPa of bleached jute reinforced composite. Impact strength of bleached jute epoxy composite (107.94 J/K) is higher than the control jute epoxy composite (94.46 J/K) (Mishra et al., 2000). Mishra et al. (2000) also studied the effect of chemical modification on the impact energy of jute/Flax/hemp epoxy composite and concluded that the modified surfaces can further bond with epoxy resin and enhanced good bonding which resulted in increased impact strength (Mishra et al., 2000).

Also observed 60 % enhancement in strength on increasing fibre volume Vf from 0.15 to 0.22 in hemp/ interfacial adhesion, through chemical bonds between the fibre and coupling agent/film former and the coupling agent/ film former and matrix. 1 wt% NaOH for 4 hours was found to be the optimal condition for the fibre surface treatment. In the combination of the silane with epoxy, the dispersion is efficient with an aliphatic silane (3-Aminopropyl-triethoxy-silane), but not with an aromatic silane (Phenylaminopropyl-trimethoxy-silane). The transverse tensile strengths of unidirectional jute/epoxy composites increased by 29%, and the transverse bending strength increased by 17% for NaOH treated

jute/epoxy composites. However, the fibre surface treatment did not significantly influence the tensile and bending modulus because of same fibre volume contents. The water absorption of the jute/epoxy composites also follows a Fickian model. The fibre surface treatments decrease the water uptake and the diffusivity of the composites compared to the untreated state (Gassan & Bledzki, 1997; Maschinenwesen et al., 2006). Mishra et al., 2000 studied the tensile, flexural and impact properties of control and bleached jute reinforced epoxy composite (JEH 50 (C) and JEH 50 (B) respectively), in which JEH 50 (B) possess a higher (107.94 j/m) Izod impact strength than that of JEH 50 (C) (94.46 j/m); that means JEH 50 (B) composite has more toughness, and hence, can resist the fracture under stress applied at high speed. JEH 50 (B) showed higher impact strength (14,701.38 j.m<sup>2</sup>) than the JEH 50 (C) (11482.14 j/m<sup>2</sup>). High impact value attributed to the better bonding between the bleached fibre and matrix. Thus, the composite becomes more hydrophobic and tougher due to delignification. Here resin replaces the role of the lignin in jute fibre epoxy composite, but jute epoxy composite showed the contrary as the impact strength decrease on further increase in volume e fraction (Mishra et al., 2000). For the epoxy matrix, fibre surface treatment by alkali, organo silane, epoxy dispersions and the combinations lead to better interfacial adhesion. Especially, the presence of coupling agent or epoxy film former, incorporated into the composites to tailor the chemical structure, leads to improved.

#### **8.1.1.4 Jute polypropylene/ polystyrene thermoplastic composite**

Earlier work on jute polypropylene composite developed using different coupling agent like Maleic anhydride grafted polypropylene (2% wt MAHgP) showed enhanced tensile strength. The interfacial shear strength increases 91% for PP1-jute composite and 68% for PP2 jute composite (jute polypropylene). Concluded that the intrinsic tensile properties of jute fibre are propositional to fibre cross sectional area associated with its perfect circle shape, the measured fibre tensile strength actually increase with jute cross sectional area at a constant gauge length. An increase of the tensile strength occurs for jute/pp composites in humidity aging conditions which are attributed to the improvement in both polymer and interfacial adhesion strength (Doan et al., 2006). Coupling agent MAHgPP (2%) in jute PP composite increases the storage modulus at 19.8% fibre content, which indicate the enhanced adhesion between fibre and matrix due to the coupling agent, leading to the better transfer of stress from matrix to the fibre (Doan et al., 2007).

Interfacial Sher Stress (IFSS) between fibre and matrix is much lower (3.49MPa) than the synthetic fibre and thermo sets. This IFSS is mainly depends on the chemical and mechanical interlocking. Untreated jute have less compatibility with matrix due to hydroxyl group presence, hence IFSS is mainly attributed to irregularity of jute fibre surfaces. Treatment improved the compatibility, hence IFSS increases. The IFSS with 2 wt% NaOH and 2 wt % KH 550 treated jute PP composite increases approximately 51%,39% and 22% than untreated Jute PP composite (Liu & Dai, 2007). In another study, effect of coupling agents on both interfacial and bulk mechanical properties of jute fibre/polypropylene composites were investigated with three kinds of maleic anhydride grafted polypropylene (MAHgPP), namely Exxelor PO 1020 (Ex), Polybond 3200 (PO) and TPPP 8012 (TP) were used as matrix modifier. Ex was found to achieve the best mechanical properties at a content of 2 wt%.

Higher molecular weight polypropylene (PP) with less melt flow rates improved the mechanical properties to a greater extent than lower molecular weight polypropylene. The

tensile modulus of jute/PP composites increased with increasing fibre content and showed less sensitivity to the variation of interfacial adhesion. Thermal behavior of the jute, PP and composites was determined differently under nitrogen and air flows. The thermal resistance of PP (High m.wt.) composites decreased with increasing fibre content in nitrogen atmosphere. However, the TG curves of these composites in air shift towards a lower temperature region and the thermal resistance of composites was found to increase with increasing fibre content. The diffusion process of water in jute/polypropylene composites followed Fickian model. An increase in moisture absorption was observed with increasing fibre content. An increase of the tensile strength occurred for jute/PP composites after humidity aging, which is attributed to the improvement in both polymer and interfacial adhesion strength. Using jute fibre as the reinforcement increased the storage modulus with increasing fibre content. However, the moisture uptake caused a decrease in the storage modulus for most temperatures and also in glass-transition temperature at the same fibre content.

| Composite             | Fibre Volume (%) | Ult Strength (Mpa) | Ult strain (%) | Tensile modulus (MPa) | Flexural strength (MPa) | Flexural Modulus (MPa) | Izod Impact strength (JK) | Charpy Impact strength (JK) |
|-----------------------|------------------|--------------------|----------------|-----------------------|-------------------------|------------------------|---------------------------|-----------------------------|
| Jute Epoxy (control)  | 50               | 148.3±<br>6.94     | 6.29±<br>0.93  | 3184±<br>620          | 155.82±<br>13.59        | 14232±<br>2216         | 94.46                     | 11482.14                    |
| Jute Epoxy (Bleached) | 50               | 131.09±<br>23,563  | 7.41±<br>0.90  | 2348±261              | 196.12±<br>18.99        | 20445±<br>2240         | 107.94                    | 14701.38                    |
| Jute epoxy            | 40               | 139.8±<br>4.59     | 7.32±<br>0.69  | 2826±146              | -                       | -                      | -                         | -                           |
| Jute Epoxy            | 50               | 148.3±<br>6.94     | 6.29±<br>0.93  | 3184±185              | -                       | -                      | -                         | -                           |
| Jute Epoxy            | 57               | 143.36±<br>4.06    | 5.98±<br>0.92  | 3060±185              | -                       | -                      | -                         | -                           |

Source: Mishra et al., (2000)

Table 8.1.1.3 Mechanical properties of Jute Epoxy composite

Generally, 10% fibre loading can increase the tensile strength of polystyrene/pp blend. Jute reinforcement increases the tensile strength as compared to coconut reinforcement, PP/PS composite, which is due to the single fibre property; means tensile strength of jute is higher than the single coconut fibre. Tensile strength of PP/PS blend (24.73 MPa) increases up to 30.99MPa after jute fibre loading explained in Table 8.1.1.4. Youngs modulus of composites with 10 % fibre loading are higher than the PP/PS composite which shows that stiffness increases after fibre addition (1.2163 GPa to 1.2244GPa). But charpy impact strength of jute addition to PP/PS blend decreases from 3.89 KJ/m<sup>2</sup>. The failure mechanism of these composite was mainly by fibre pull out due to the weakness of interfacial strength between fibre and matrix. Impact energy is dissipated by deboning, fibre and matrix fracture and fibre pull out (Hatta et al., 2008).

| Type of Composite   | Fibre Volume (%) | Tensile Strength (MPa) | Youngs Modulus (Gpa) | Impact strength        | Flexural Strength (MPa) | Reference            |
|---|------------------|------------------------|----------------------|------------------------|-------------------------|----------------------|
| Jute fibre Mat polypropylene Composite                    |                  | 28.4±0.90              | -                    | 65±3.2 j/m             | 35.1±1.2                | Liu & Dai, (2007)    |
| Pure Polypropylene + pure Polystyrene (50/50)             | 0                | 24.73±0.99             | 1.1745               | 3.89 KJ/M <sup>2</sup> | -                       | Hatta et al., (2008) |
| Pure Polypropylene + pure Polystyrene (50/50) + 10% fibre | 10               | 30.99±0.85             | 1.2163               | 3.11 KJ/M <sup>2</sup> | -                       | "                    |

Table 8.1.1.4 Mechanical properties of jute -Polypropylene/Polystyrene composite

## 8.1.2 Sisal composite

### 8.1.2.1 Sisal polyester composite

Most of the physico-mechanical properties of composites made from fibres are shown in Table 8.1.2.1. The density of these composites is 0.99 to 1.12 g/cm<sup>3</sup>. The results indicate that there is no appreciable change in density with respect to the surface-modifying agents. The void contents of surface treated fibre samples are lower than those of untreated ones; silane-treated samples are the lowest. It has been reported that voids, even in small amounts, are detrimental to the mechanical properties of polymer composites. The surface modification of sisal fibres caused a modest improvement of 15 to 33% in tensile strength, 45 to 79% in tensile modulus and 21 to 29% in both flexural strength and flexural modulus (silane-treated samples showed an improvement of 62% in flexural properties). This improvement indicates improved fibre-matrix adhesion (Felix et al., 1993). The interface formed is much less stiff than the resin matrix and provides a deformation mechanism to reduce interfacial stress concentration. Further, it may also prevent fibre-fibre contacts, which are sources of high stress concentrations in the final composites (Kardos et al., 1985).

| Composite                 | Fibre Vol (%) | Density g/cm <sup>3</sup> | Tensile strength (MPa) | Elongation (%) | Tensile Modulus (GPa) | Flexural Strength (MPa) | Flexural Modulus (Gpa) | Reference              |
|---------------------------|---------------|---------------------------|------------------------|----------------|-----------------------|-------------------------|------------------------|------------------------|
| Sisal Polyester composite | 50            | 0.99                      | 29.66                  | 9.52           | 1.15                  | 59.57                   | 11.94                  | Singh et al., (1996)   |
| Polyester neat composite  | -             | -                         | 22.5                   | 1.8            | 1.39                  | -                       | -                      | Fonseca et al., (2004) |

Table 8.1.2.1 Physico Mechanical Properties of Sisal-Polyester composite

Elongation at break of silane-treated composites is lower than that of the others. The high energy to break off surface-treated composites indicates that the matrix is controlling the growth of cracks as fracture proceeds. Work carried out by Fonseca et al., (2004) showed that sisal polyester composites resulted a tensile strength, tensile modulus, impact strength of 7 MPa, 1.7GPa and 328±65 respectively. However, the elongation at break (1.7%) found to be higher than that of the similar polyester sisal composites as reported by Singh et al., (1996). A 69% decrease on tensile strength and a 46% decrease on elongation at break were



observed with sisal addition for the polyester- sisal composites. A weak fibre-matrix interface was expected for this composite, since no fibre treatment or matrix modification was performed. The weak interface and the low fibre volume fraction employed are held responsible for the low mechanical properties and premature failure of that composite (Fonseca et al., 2004).

### 8.1.2.2 Sisal epoxy composite

Incorporation of the sisal fibre significantly increase the tensile strength and Young's modulus of the epoxy resin composite (46% (v/v) and is summarized in Table 8.1.2.2. As reported by sisal epoxy composite showed a Young's modulus of about 20GPa and tensile strength of 210 MPa. Flexural modulus of unidirectional sisal- epoxy composites showed 16GPa (40%v/v) (Bisanda & Ansell, 1991) and flexural strength was 266 MPa. For nonwoven sisal mats, Singh et al., (1996) reported that sisal-polyester composites (50% v/v) had a tensile strength of 30 MPa and a tensile modulus of 1.15 GPa for which composites were manufactured by impregnation of the nonwoven sisal mats and then compression moulded during 2 h (Oksman et al., 2002). The tensile behavior of the sisal reinforced composites is illustrated by Fonseca et al., (2004). Sisal addition increased (20%) young's modulus of unmodified polyester (SP) with the respective matrices. This behavior was expected, since sisal fibres have higher young's modulus than both the unmodified and the flame retardant modified matrices. The uniform increases in modulus values for these two composites are in accordance with the fact that the volume fraction of fibres in both composites was equivalent. Another important mechanical property i.e. impact strength of sisal epoxy composite were analyzed by Rong et al., (2002) and it was found in the range of 65 - 80 Kj/m<sup>2</sup>. Silane treated matrix (SM) composites resulted caused a marked increase on its tensile modulus. This behavior is thought to be due to an enhancement on fibre/matrix adhesion, caused by the incorporation of the silane coupling agent.

| S. No. | Composite             | Fibre Volume (%) | Tensile strength (MPa) | Elongation at break (%) | Tensile Modulus (GPa) |
|--------|-----------------------|------------------|------------------------|-------------------------|-----------------------|
| 1.     | Epoxy                 | 0                | 76                     | 7.3                     | 3.1 - 3.2             |
| 2.     | Sisal Epoxy composite | 28               | 169±23                 | 2.3                     | 14.2±1.6              |
| 3.     | Sisal Epoxy composite | 35               | 183±16                 | 2.2                     | 14.5±1.6              |
| 4.     | Sisal Epoxy composite | 46               | 211±12                 | 1.9                     | 19.7±1.5              |

Source: Oksman et al., (2002)

Table 8.1.2.2 Mechanical Properties of Sisal Epoxy Composite

### 8.1.2.3 Sisal Urea formaldehyde composite

Mechanical properties of Sisal fibre reinforced urea-formaldehyde resin composites were investigated by Zhong & Wei, (2007), Table 8.1.2.3. The composite with 50% (w/w) sisal fibre showed optimal charpy impact strength (9.42kJ/m<sup>2</sup>). Whereas the flexural strength, wear resistance and water absorption properties are proved to be excellent in the composite with 30% (w/w) sisal fibre under the present experimental conditions adopted. The fibres

themselves possess a higher wear resistance than the matrix and should protrude from the SEM surface that these composites in fibre board can be expanded (Zhong & Wei, 2007).

| S.No. | Fibre volume (%) | Charpy Impact strength (Kj/m <sup>2</sup> ) | Flexural Strength (MPa) | Flexural Modulus (Gpa) | Density (g/cm <sup>3</sup> ) |
|-------|------------------|---|-------------------------|------------------------|------------------------------|
| 1.    | 30               | 5.75  | 58.58                   | 7.63                   | 1.53                         |
| 2.    | 40               | 6.5   | 55.80                   | 5.27                   | 1.52                         |
| 3.    | 50               | 9.5   | 53.07                   | 4.93                   | 1.48                         |
| 4.    | 60               | 7   | 37.73                   | 4.09                   | 1.44                         |
| 5.    | 70               | 6.8   | 15.28                   | 1.59                   | 1.22                         |

Source: Zhong & Wei, (2007)

Table 8.1.2.3 Mechanical Properties of Sisal - Urea formaldehyde composite

#### 8.1.2.4 Sisal polystyrene / polypropylene composite

Polystyrene with maleic anhydride (PSMA), toluene diisocyanate (T'DI), methyl triethoxy silane and triethoxy octyl silane) on sisal fibre were tried to improve its efficiency as reinforcement in polystyrene-sisal fibre composites. All fibre modifications improve the tensile properties of the composite. The decreased in hydrophilicity of the treated fibre and increased thermodynamic compatibility of the treated fibre with the polymer matrix are responsible for the improvement in the mechanical properties (Nair et al., 2003). The maximum improvement in tensile properties was observed with PSMA coating (Table 8.1.2.4). In all cases except PSMA coating, fibre modification decreases the impact strength of the composites and PSMA coating showed an improvement in the impact strength. Flexural strength of treated composites exhibits an improvement in all cases except benzylation. Flexural modulus showed a decrease in both benzyolated and toluene diisocyanate treated fibre composites and an improvement in the case of silane treated fibre composite. PSMA treated fibre composite, however, shows no considerable variation in flexural modulus. Flexural strain also showed no considerable variation with fibre modification (Nair et al., 2003).

| Composite                    | Fibre volume (%) | Tensile strength (MPa)approx | Flexural Strength (Mpa) | Impact strength (Jm) | Reference              |
|------------------------------|------------------|------------------------------|-------------------------|----------------------|------------------------|
| Polystyrene                  | 0                | 35                           | 48                      | -                    | Nair & Thomas, (2003)  |
| Untreated sisal PS composite | 0                | 43                           | 72                      | -                    |                        |
| Sisal-PP                     | 0                | 17.80                        | 19.60                   | 23.25                | Mohanty et al., (2004) |
| Sisal-PP                     | 6.8              | 24.17                        | 34.83                   | 40.50                |                        |
| Sisal-PP                     | 10.3             | 26.11                        | 46.35                   | 46.10                |                        |
| Sisal-PP                     | 21.0             | 29.25                        | 48.96                   | 51.79                |                        |
| Sisal-PP                     | 31.0             | 23.21                        | 43.41                   | 39.83                |                        |

Table 8.1.2.4 Mechanical properties of sisal Polypropylene (PP)/Polystyrene (PS) Composite

The mechanical and dynamic mechanical properties of PP-sisal fibre composites have been investigated and summarized in Table 8.1.2.4. It was observed that the composites prepared with 21% fibre content with 1% MAPP concentration showed optimum mechanical strength. Storage modulus versus temperature plots showed an increase in the magnitude of the peaks with the addition of fibres and MAPP. The damping properties of the composites, however, decreased with the addition of the fibres and MAPP. Based on these studies, it can be concluded that sisal fibres could reinforce the PP matrix when used in optimal concentration of fibres and coupling agents (Mohanty et al., 2004).

### 8.1.3 Flax composite

#### 8.1.3.1 Flax polyester composite

The mechanical properties of short fibre reinforced composites are expected to depend on the intrinsic properties of both matrix and fibre, on aspect ratio, content, length and fibre-matrix adhesion that is responsible for the efficiency of load transfer in the composite. In flax polyester composite, tensile modulus  $E$  increase with fibre content as shown in Table 8.1.3.1. Tensile strength of polyester composite tends to 20 MPa to 21 MPa at 12.5 % flax loading, 19.4 MPa at 25% flax loading and decreases at 37.5% loading (16.2%). Critical fibre length also affect the stress transfer from fibre to matrix, means critical fibre length is inversely proportional to the interfacial strength (Baiardo, 2004). Bledzki et al., (2008) studied the effect of acetylation on mechanical properties and found tensile and flexural strength of composite increase with increasing the degree of acetylation and contrary to it, Charpy impact strength of composite were found to decreased with increasing degree of acetylation (Bledzki, 2008). Marais et al., (2005) worked out the cold plasma treatments on mechanical properties of unsaturated polyester composite. The mean value of tensile modulus, tensile specific modulus, breaking strength, breaking strain of untreated pure resin and composite were determined. The value of the tensile specific modulus and breaking strength of the reinforced composite higher than for the polyester, matrix (Marais, 2005).

| S. No. | Composite      | Fibre volume (%) | Breaking strength (MPa) | Breaking strain (%) | Youngs Modulus (MPa) |
|--------|----------------|------------------|-------------------------|---------------------|----------------------|
| 1.     | Polyester      | 0                | 20.0                    | 19.6                | 435                  |
| 2.     | Flax polyester | 12.5             | 21.7                    | 14.1                | 760                  |
| 3.     | Flax polyester | 25               | 19.4                    | 6.1                 | 1112                 |
| 4.     | UPR            | -                | 70                      | 2.2                 | 3.7                  |
| 5.     | Flax composite | -                | 1150                    | 3                   | 70                   |

Source: Baiardo et al., (2004)

Table 8.1.3.1 Mechanical properties of flax Polyester composite

#### 8.1.3.2 Flax epoxy composite

Modulus of epoxy resin is 2909MPa whereas the flax fibre has low modulus. The mechanical properties depend on defects and dispersion in geometry of fibres. The fibre has a polygonal cross section that contains many defects along their length. Lamy & Pomel, (2002) determine the modulus  $E_1$  of unidirectional flax epoxy composite using equation below for a fibre

volume fraction 40% and compared with experimental results (Table 8.1.3.2). Longitudinally flexural modulus  $E_1$  is 12000 MPa, for unidirectional composite and measured modulus of the woven flax reinforced composite is 3500 MPa (Lamy & Pomel, 2002).

| S.No. | Composite   | % Fibre | Thickness (mm) | Flexural stiffness (J) | Flexural Modulus |
|-------|-------------|---------|----------------|------------------------|------------------|
| 1.    | Flax Epoxy  | 34      | 2.28±0.01      | 82900±1800             | 3500±150         |
| 2.    | Glass Epoxy | 50      | 1.03±0.01      | 41800±900              | 19000±1000       |

Source: Lamy & Pomel, (2002)

Table 8.1.3.2 Flexural strength of flax epoxy composite

### 8.1.3.3 Flax Polystyrene composite

Tensile strength of a material is the maximum amount of tensile stress that can be subjected to before it breaks. Polystyrene blend show tensile strength (125N/mm<sup>2</sup>) enhancement of raw flax fibre loading to 175 N/mm<sup>2</sup> and extension increases up to 4.3 mm shown in Table 8.1.3.3. Grafting with MMA on flax increases the water resistance because MMA has less water affinity (Kaith et al., 2008).

| Composite         | Compressive strength (N/mm <sup>2</sup> ) | Compression | Tensile strength (N/mm <sup>2</sup> ) | Extension |
|-------------------|---|-------------|---------------------------------------|-----------|
| PS                | 100±5.5                                   | 00.27±0.02  | 125±3.6                               | 0.42±0.05 |
| Flax PS composite | 400±3.6                                   | 0.9±0.04    | 175±4.6                               | 4.3±0.01  |

Source: Kaith et al., (2008)

Table 8.1.3.3 Mechanical properties of Flax Polystyrene (PS) composite

### 8.1.3.4 Flax polypropylene composite

MAPP (Maleic Anhydride polypropylene) treatment were done and it was found that flexural strength of flax pulp and fibre PP composite is higher than that for neat polypropylene blend because the fibres have higher stiffness than polymer. Flax fibre always has higher mechanical properties than the fibre pulp and treatments vary the modulus, this is due to the -OH adsorption bands. Neat PP blends have less flexural strength than the all composite containing fibre shown in the results of Table 8.1.3.4. MAPP containing polypropylene chain smooth the different surface energy values of matrix and fibre, increases better wetting of fiber and the interfacial adhesion. Composites made with a 10 wt % MAPP treated fibre have the highest flexural and tensile strength (Cantero et al., 2003).

| Composite | Tensile strength (MPa) | Tensile Modulus (MPa) | Charpy strength (mj/mm <sup>2</sup> ) | Impact | Flexural strength (MPa) | Flexural Modulus (MPa) | Reference              |
|-----------|------------------------|-----------------------|---------------------------------------|--------|-------------------------|------------------------|------------------------|
| PP        | 27                     | 700                   | -                                     |        | 35                      | 1400                   | Cantero et al., (2003) |
| Flax PP   | 19                     | 17500                 | -                                     |        | 48                      | 3400                   |                        |
| Flax PP   | 39                     | 4200                  | 19                                    |        | 56                      | 3800                   | Bledzki et al., (2008) |

Table 8.1.3.4 Mechanical properties of Flax Polypropylene (PP) composite

### 8.1.4 Cotton composite

The work done by Gohil & Shaikh, (2010) discussed the variation in composite strength as a function of fibre volume ( $v/v$ ) for longitudinally placed cotton fibre with polyester resin. The composite strength with polyester resin is summarized in Table 8.1.4. It is observed that composite strength in the range of 27.94 MPa to 71.16 MPa for longitudinally placed cotton fibre with 10.41% to 35.27%. The variation in composite elastic modulus as a function of  $f v$  for longitudinally placed cotton fibre with polyester resin is observed in the range of 2.70GPa to 4.04GPa for longitudinally placed cotton fibre adjacent to the  $f v$  range of 10.41% to 35.27%. The experimental investigation indicates that, as the fibre volume fraction increases the strength as well as longitudinal elastic modulus increases linearly. This is inline with the rule of mixture which predicts the linear increase in composite strength with increase in volume fraction of fibres holds true for longitudinally placed fibre composite for all the fibre matrix combination (Gohil & Shaikh, 2010) (Table 8.1.4).

| S. No. | % Fibre volume | Tensile Strength (MPa) | Elastic Modulus (GPa) |
|--------|----------------|------------------------|-----------------------|
| 1.     | 10             | 28                     | 2.8                   |
| 2.     | 20             | 45                     | 3                     |
| 3.     | 25             | 53                     | 3.4                   |
| 4.     | 28             | 62                     | 3.6                   |
| 5.     | 35             | 72                     | 4                     |

Source: Gohil & Shaikh, (2010)

Table 8.1.4 Tensile properties of Cotton polyester composite

## 8.2 Properties of animal fibre composite

### 8.2.1 Wool composite

Results indicate that there is little influence on the tensile stress or modulus of elasticity with increasing fraction of wool content. However, when the fibres were laid in a transverse position to the tensile load, the tensile stress was increased. The modulus of elasticity of the transverse samples was similar to that of the parallel fibre samples. The influence of apparent fibre orientation is again indicated where the transverse toughness values are one-third of the longitudinal values. This implies that wool may be able to provide reinforcement in multi-axial situations (Blicblau, 1997). The mechanical properties of raw wool polyester resin composite are shown in Table 8.2.1.

| S. No. | Wool (wt %) | Tensile strength (MPa) | Tensile modulus (MPa) | Flexural strength (MPa) | Izod impact toughness |
|--------|-------------|------------------------|-----------------------|-------------------------|-----------------------|
| 1.     | 0           | 33.7 ± 4.2             | 0.7 ± 0.2             | -                       | -                     |
| 2.     | 22          | 35.9 ± 3.3             | 3.2 ± 0.2             | 76.2 ± 6.3              | 9.2 ± 1.3             |
| 3.     | 37          | 34.6 ± 2.6             | 2.7 ± 0.3             | 72.1 ± 6.2              | 46.7 ± 15.8           |
| 4.     | 51          | 39.1 ± 1.7             | 1.6 ± 0.2             | 75.4 ± 6.3              | 49.9 ± 10.4           |
| 5.     | 54          | 40.7 ± 1.2             | 1.8 ± 0.1             | 7.5.1 ± 1.3             | 58.1 ± 9.3            |
| 6.     | 54          | 17.1 ± 1.2             | 1.3 ± 0.1             | 54.7 ± 0.9              | 25.1 ± 0.6            |

Source: Quazi et al., (2010)

Table. 8.2.1 Mechanical properties of raw wool-polyester resin composites

### 8.2.2 Silk composites

Silk fibre reinforced composite materials comprising a thermoplastic polymer matrix, which are relatively light whilst having a high impact resistance. Due to the high impact resistance of the fibrous composite material, panels or shells comprising such composites are particularly useful for the manufacture of objects which in the course of their life cycle are subject to shocks or at risk of penetration (Patent; Silk fibre composites, Washington, DC, US, 2010). There is a growing interest in the use of composite materials. Silk fibre/ gelatin bio-composites were fabricated using compression molding. *Bombyx mori* woven natural silk is among the strongest fibres produced in nature. It has high specific-strength and high specific-stiffness; extremely elastic and resilient (Bledzki & Gassan, 1999). Perez-Rigueriro et al., (2000) showed that *Bombyx mori* silk is better than Kevlar or steel in terms of elongation at failure. It has a good capacity to absorb energy and to dissipate this energy in a very controlled manner as the silk deforms (Perez-Rigueriro et al., 2000). The interlacing of fibre bundles in woven fabrics composites prevents the growth of damage and hence provides an increase in impact toughness compared with unidirectional composites.

Silk woven fabrics composites are easy to handle and have excellent formability (Dasgupta & Agarwal, 1992). The tensile strength (TS) and bending strength (BS) with varying silk content of the composite. TS and BS increased with the increase of fibre content and were found maximum in this experiment for 30% fibre. TS and BS of composite with 30% silk content showed 54 MPa and 75 MPa, respectively, whereas the 0% silk content gelatin film showed the TS and BS of 32 MPa and 47 MPa, respectively. At low fibre content, the composites showed poor TS and BS. This is because of higher matrix content and attribution of low load transfer capability by low fibre content. With the increase of fibre content from 10 to 30%, load transfer capability also increases and greater TS and BS results. The tensile modulus (TM) and bending modulus (BM) of the composites were found to increase on increasing silk content signifying that the stress transfers from the gelatin matrix to the stiffer fibre occurred.

### 8.2.3 Human hair composites

Investigations on the mechanical properties of human hair and its composites are inadequate. The most important mechanical property of hair is its elasticity. According to Hooke's law, when an elastic fiber is pulled, the change in length is proportional to the force applied. The elasticity of wet and dry hair is directly proportional to shaft diameter. Hair diameter is the most important factor for hair mechanics (Franbourg et al., 2003; Dawber & Messenger, 1997). The physical properties of hair can be divided into elastic deformations including stretching, bending, stiffness, torsion, cross sectional area and shape, density, friction and static charge (Dawber & Messenger, 1997). Bleaching alters the elasticity of hair, and decreases its tensile properties by up to 25% (Dawber & Messenger, 1997). The hairs were dyed or un-dyed did not affect the mechanical properties of hairs. If there is a connection between the mechanical properties of human hair and its durability, it is possible to alter the properties of hair. The mechanical properties of human hairs would effects on protein structure,  $\alpha$ -keratin fibres and microfibril- and matrix composite behaviours (Berivan et al., 2008). So there is lot of scope for new studies on composites development using human hair which may result in a new materials with better performance leading to effective recycling/ utilization of human hair for value added engineering application.

### 8.2.4 Feather fibre composites

Hong and Wool (2005), studied the bulk density of feather fibre soy resin matrix composites. Composite bulk density of 1.08 g/cm<sup>3</sup> was higher than expected (1.001 g/cm<sup>3</sup>) for the composite containing 30% wt feather fibre. The higher bulk composite density could also be explained by a higher value for the apparent density of feather fibre. However, yet very limited work has been reported on feather fibre composites. The effects of various blends of cement and feather on the hygroscopicity and dimensional stability were measured using water absorption and thickness swelling tests. These tests were determined by submerging specimens horizontally in water at room temperature for two and 22 hours. After each submersion period, samples were drained of excess water and measured for change in thickness and amount of water absorbed. Thickness swelling was measured from two marked points along the length of each sample with a digital sliding caliper. Water absorption and thickness swelling were expressed as a percentage of the original weight and thickness, respectively (Menandro & Acda, 2010). The effects of different formulations on board stiffness and flexural strength were evaluated using a three point bending test, with some modifications.

### 8.3 Properties of Mineral fibre composites

Many building product have been made from asbestos fiber such as tiles, sheet, corrugated roofing element, sheets, pipes, etc., mostly these materials were made using asbestos fiber with cement. Asbestos cement products contain 8-16 % of asbestos fibre by volume. Shah, 1981 used two type of asbestos fibre Chrysotile and Crocidolite for comparison of their strength and found crocidolite asbestos cement composites strength was more than chrysotile cement composites. Asbestos mechanical properties of cement composites are shown in Table 8.3.1. Sung et al., (1975) was studied on asbestos reinforced with phenolic resin which resulted flexural strength of 93.76MPa, flexural modulus of 159.96GPa and impact strength of 64.08j/m. Akers & Garrett, (1983) studied on the failure process of asbestos-cement composites and calculates the flexural strength (35-37 MPa). Lee et al, (2004) used different orientation of asbestos fiber in phenolic composites and reported that in axial position of fiber in composites showed maximum tensile strength but of compressive strength was maximum in radial position. Asbestos mechanical properties of cement composites are shown in Table 8.3.2. Akers & Garrett, (1986) has reported that when fibre mass fraction increased modulus of rapture is also increase up to 15 %. Addition of more than 20 % asbestos fiber decreased the modulus of rapture but decreased the density from 1.65 g/cm<sup>3</sup> to 1.23 g/cm<sup>3</sup> when 35 % fiber was added, however the impact strength was increased with increased in fiber content. Asbestos mechanical properties of cement composites are shown in Table 8.3.3 and Table 8.3.4. When water cement ratio varies in

| S. No. | Type of composites                     | Tensile strength (MPa) | Young's Modulus of elasticity (GPa) | Density | Elongation of break(%) |
|--------|--|------------------------|-------------------------------------|---------|------------------------|
| 1.     | Chrysotile Asbestos cement composites  | 3100                   | 16.4                                | 2.55    | 2-3                    |
| 2.     | Crocidolite Asbestos cement composites | 3500                   | 19.6                                | 3.37    | 2-3                    |

Source: Shah, (1981)

Table 8.3.1 Physico- mechanical properties of Asbestos cement composites

asbestos cement composites, modulus of rupture (MOR) also varied and it is maximum at 0.33 water cement ration but when water cement ratio increase from 0.33, the mechanical properties is also decreased. Optimum water-cement ratio need to be maintained about 0.33, where maximum strength can be achieved (Akers & Garrett, 1986).

| S.No. | Orientation of fibre              | Tensile strength (MPa) | Tensile modulus (GPa) | Compressive strength (MPa) |
|-------|-----------------------------------|------------------------|-----------------------|----------------------------|
| 1.    | Hoop                              | 82                     | 13.3                  | 86.2                       |
| 2.    | Radial<br>(orientation of fibre ) | 11.1                   | 3.0                   | 105.3                      |
| 3.    | Axial<br>(orientation of fibre )  | 15.6                   | 3.5                   | 75.3                       |

Source: Lee & Kim, (2004)

Table 8.3.2 Mechanical properties of Asbestos Phenolic Composite

| S. No. | % Fibre mass fraction | Modulus of rapture (N/mm <sup>2</sup> )<br>(no pressure ) | Impact resistance (KJm <sup>2</sup> ) | Density (g/cm <sup>3</sup> ) |
|--------|-----------------------|---|---------------------------------------|------------------------------|
| 1.     | 5                     | 20-24   | 0.6- 1.4                              | 1.65                         |
| 2.     | 10                    | 35-40   | 2.0 -2.4                              | 1.55                         |
| 3.     | 15                    | 37-42   | 2.2 – 3.0                             | 1.45                         |
| 4.     | 20                    | 33-37   | 3.0 – 3.5                             | 1.3                          |
| 5.     | 25                    | 25-30   | 3.5-3.8                               | 1.25                         |
| 6.     | 30                    | 25-30   | 3.5-3.8                               | 1.23                         |

Source: Akers & Garrett, (1986)

Table 8.3.3 Physico Mechanical properties of asbestos fibre cement composites (Different % fibre content)

| S. No. | Water cement ratio | Modulus of rapture (N/mm <sup>2</sup> )<br>(no pressure ) | Impact resistance (KJm <sup>2</sup> ) | Density (g/cm <sup>3</sup> ) |
|--------|--------------------|---|---------------------------------------|------------------------------|
| 1.     | 0.30               | 30-32   | 0.8-1.2                               | 1.65                         |
| 2.     | 0.33               | 32-35   | 1.2-1.4                               | 1.55                         |
| 3.     | 0.35               | 25-30   | 1.0-1.3                               | 1.45                         |
| 4.     | 0.37               | 23-25   | 1.2-1.4                               | 1.3                          |
| 5.     | 0.40               | 20-25   | 0.8-1.2                               | 1.25                         |
| 6.     | 0.45               | 15-20   | 0.4-0.8                               | 1.23                         |
| 7.     | 0.50               | 10-15   | 0.2-.06                               | -                            |

Source: Akers & Garrett, (1986)

Table 8.3.4 Physico Mechanical properties of asbestos fibre cement composites (Variation in water cement ratio)



## 9. Opportunities and challenges

Natural fibres have gained much interest among technologists and scientist for applications in civil, military, industrial, space craft and biomedical sectors (Saheb & jog, 1999). In the past two decades, growing interest for natural fibres composites has resulted in extensive research. The driving forces are (i) cost reduction, (ii) weight reduction and (iii) marketing (application of renewable materials). Technical requirements were of less importance; hence application remained limited to non-structural parts for a long time. The reason for this is the traditional shortcomings of NF composites, the low impact resistance and moist degradation. Recent research however showed that significant improvements of these properties are possible. The scope of different natural fiber composites and feature challenges and discussed with following section.

### 9.1 Plant fiber

The use of plant fibres as reinforcement in composite materials is finding increasing interest in the automotive and building industry, and the properties of plant fibre composites have been addressed in numerous research studies. New composite materials based on plant fibres and polymers are being increasingly used in the building industry and in automotive industry. Plant fibres, such as sisal, jute, hemp, flax, palm etc can be used as reinforcement for Epoxy, polyester, PVC, PE or PP-type polymers in place of synthetic fibres (glass, Kevlar, carbon, etc.). This substitution offers many benefits:

- Economic: lower costs on account of significantly reduced cycle times, energy savings.
- Technical: mechanical properties identical to those of traditional reinforcements, reduced tool wear and tear, high geometric stability of the manufactured parts, good insulation characteristics;
- Environmental: renewable resource, easy to recycle, no material toxicity, reduced fossil fuels content, CO<sub>2</sub>-neutral materials.

Natural fiber composite materials are being used for manufacturing many components in the automotive sector (Taj et al., 2007; Karus & Gahle, 2006; Saxena et al., 2008, 2011; Mohanty et al., 2005; Xin et al., 2007). Like glass, the natural fibers combine readily with a thermoplastic or thermosetting matrix to produce commodity goods (Brouwer, 2002). Typical market specification natural fibre composites includes ultimate breaking force and elongation, impact strength, flexural properties, acoustic absorption, fogging characteristics, flammability, and suitability for processing: temperature and dwell time, odor, water absorption, dimensional stability, and crash behavior (Mohanty et al., 2005). Plant fibers are mainly used in the interior parts making of passenger cars and truck cabins. Such insulating materials, mainly based on cotton fibers recycled from textiles, have relatively high fiber content of more than 80% by weight. Brazilian trucks trim parts were made of a mixture of jute, coffee bag wastes, and polypropylene bags show that recycling sometimes can lead to advanced applications (Bledzki & Gassan, 1999). The use of plant fiber based automobile parts such as trim parts, various panels, shelves, and brake shoes are attracting automobile industries worldwide because of its reduction in weight of about 10%, energy production of 80%, and cost reduction of 5%. Conservative estimates indicate that about 6,000 TPA plant fiber-based composite parts can find their way into passenger cars and multi-utility vehicles (Saxena et al., 2005, 2011).

Prospects for the use of plant fiber in Automotive locomotive, aerospace, construction industry has long way to go to meet the societal area. In railways, the gear case, main doors,

luggage racks, floor/roof panels, berths, chair backings, interior panels and partitions, interior furnishing and seating, modular toilets, and lightweight coaches are made from different natural fiber composites and their combinations. Composite materials offer some significant advantages to metals in many structural applications in railways to the effect that they are lightweight, cost-effective, corrosion resistant, energy saving (Saxena et al., 2011). Development of biodegradable materials as an alternative to synthetic materials such as glass fiber-reinforced plastics and other synthetic plastics is the challenge for the present and future generations in the context of global climate change. Moreover, there are various problems associated with synthetic polymer composites due to the inherent problem of life cycle assessment and waste management at the end of its service life. At this juncture, biodegradable materials offer significant advantages provided they are techno-economically viable. Worldwide, considerable work is being done by several researchers for the development of biodegradable polymers leading to manufacturing of biodegradable polymer composites for various engineering applications (Lu, 2004; Oudshoorn, 1995).

## 9.2 Animal fibre

Applications of animal fibres in composites have not yet been exploited fully. But yet no precise method available to identify and differentiate the fibres quantity. They are often adulterated during marketing. Animal based natural fibres can also be used as alternatives for producing composite materials which may have great scope in value added application including bio-engineering and medical applications. The contents of these fibres are mainly made by proteins, like wool, spider and silkworm silk. Wool is the most popular natural material. In the textile industries, a lot of waste wool fibres and their products induce actions which lead to the regeneration of wool keratin materials. However, the most significant limitations may be the poor fracture resistance of neat keratin materials. Rock Wool Composite panel (rock wool sandwich board) is one such example for animal fiber composites. It has good fire-resistance and noise-absorbing properties. The silk fibres are environmentally stable as compared to the proteins because of their extensive hydrogen bonding. Silk fibre composites is expected to be light weight and very tough with good impact strength bearing materials. It can be shaped into complex shapes with suitable matrix. Though formed to that of synthetic fiber composites. Improvement of interface needs attention, mechanical performance.

Animal fibre reinforced composite materials have found applications in the automotive, aerospace and sports equipment industries. Compared to most metals and unreinforced plastics, animal fiber composites may offer a high strength-to-weight ratio, corrosion and termite resistant. Advantage of animal fiber composite materials is that they can be tailored to meet the specific structure. Composites may expect to be cost competitive and a very attractive alternative to conventional materials. Further the feathers take up a lot of space in landfills and take a long time to decay because of the keratin proteins that make up the feathers. There is also the fear of bird flu, which makes converting feathers into animal feeds undesirable. The cement-bonded feather board developed is more resistant to decay and termite attack due to the keratin, Feather boards could be used for paneling, ceilings and as insulation but not for weight-bearing building components like walls or pillars. Thus use of feather in composites would be an attractive and better alternative for safe management especially in value added engineering.

### 9.3 Mineral fibre

Asbestos fibres have been used for the fabrication of corrugates roofing, sheet, pipeline wrapping, electrical insulation, etc. Asbestos textiles, comprising yarn, thread, cloth, tape, or rope, also found broad application in thermal and electrical insulation and friction products in brake or clutch pads. Chrysotile has been used in asbestos-cement generally because it is cost-effective and has good mechanical properties. Asbestos has been durable and heat and oil resistant so it is incorporated into friction materials (e.g. brake linings). The asbestos fibres combine with various types of natural or synthetic resins to the development of a variety of products and applications. In asbestos fibres mainly chrysotile was used into rubber matrices yields materials that were used fabrication of packings and gaskets and heavy task insulation components as a compressed board with or without silicone resin impregnation.

Asbestos fibres also have found broad application as reinforcing agents in coatings and adhesive formulations. In the United States, the major use of asbestos fiber in roofing compounds (62%), gaskets (22%), and friction products (11%). Some quantity of asbestos also is used for manufacture insulation products and woven and plastic products (Encyclopedia of Earth home page, 2011). Asbestos composites have a broad range of applications in various industries (marine, railway, and automotive, aerospace and general engineering industries). Asbestos cloth or fibre impregnated with resins and cured under heat and pressure to fabricate sheets, rods, tubes and shaped mouldings. Asbestos causes serious health hazards, which include a range of lung, eye, and skin diseases. Thousands of deaths in the twentieth century cause by Asbestos. In many developed countries today, asbestos-related deaths are the occurred at the place of work. Asia, being the largest consumer of asbestos concern (Handbook of composites reinforced, wiley-vch, 1993). In recent years, use of asbestos in many applications has decreased, due to various environmental concerns.

| Asbestos Product  | Substitute Products  |
|---|--|
| Asbestos-Cement<br>Corrugated Roofing                         | <ul style="list-style-type: none"> <li>• Vegetable fibres in asphalt Slate</li> </ul>  |
| Asbestos-Cement Flat Sheet<br>(ceilings, facades, partitions) | <ul style="list-style-type: none"> <li>• Fibre-cement using vegetable/cellulose fibres</li> <li>• Softwood frame with plasterboard or calcium silicate board facing</li> </ul> |
| Asbestos-Cement Pipe  | <ul style="list-style-type: none"> <li>• Cellulose/PVA fibre-cement pipe</li> <li>• Cellulose-cement pipe</li> </ul>   |
| Asbestos-Cement Water Storage<br>Tanks                        | <ul style="list-style-type: none"> <li>• Cellulose-cement</li> <li>• PVA-cellulose fibre-cement</li> </ul>   |

Source: Castleman, (2009); Soyowanna, home page, (2011).

Table 9.3.1 Asbestos Substitute Products

## 10. Conclusions

Due to various environmental concerns natural fibre has been gaining special attention of technologist, engineers, industrial and manufacture for its enormous potential for

application in different engineering utility in the area of building construction, railway, automotive, packaging, defence etc. Further, natural fibre composite is cost effective, low density, renewable material, environment friendly and reduces CO<sub>2</sub> evolution. These natural fibres have been in use as reinforcing agent in polymeric, cement, matrix to increase the physical, mechanical/engineering properties. Plant, animal and asbestos fibre are the main class of natural fibres which are extensively used in product development and manufacturing. Among them, plant fibres percentage use is much higher than the animal and asbestos fibres, due to its renewability, recyclability, availability, environment friendliness. Utilization of animal fibre in composite making is an emerging area, because waste animal fibre can be utilized in useful technical application, whereas asbestos fibre has attractive mechanical, thermal, acoustic properties which can enhance its use in engineering application. But due to its carcinogenic nature many developed and developing country prohibited its use because this causes various types of diseases. So researchers are eager to develop alternative to traditional asbestos reinforced composite materials.

Animal fibres are not yet been exploited and can be used as a reinforcing medium for composite making. Composite manufacturing in this area is limited due to availability of fibre but it is emerging area of feather research. Moreover the resultant products will lead to convert the waste into wealth. Tensile strength of wool and silk is 125-200 MPa and 650-750 MPa respectively and its composite showed tensile strength 30-55 MPa. Huge range of plant fibre with wide variation in their physical, chemical and mechanical properties were found in nature and can be enhanced by different genetic and biotechnological route. Tensile strength of different plant fibres were found in the range of about 650MPa with varying density from 0.2-2 g/cm<sup>3</sup>. Series of composite of different plant fibre with different matrix has been made and utilized in different applications. Advantage of using natural fibre in composites is that they would be sustainable, biodegradable and bio-derived. It is therefore suggested that biodegradable / bio-derived matrix should be developed to meet the future challenges to safeguard nonrenewable resources and comply with Kyoto protocol for sustainable environmental sound management and save our mother earth.

## 11. Acknowledgement

The authors are thankful to Dr. Anil K. Gupta, Director, Advanced Materials and Processes Research Institute (AMPRI) Bhopal, Council of Scientific and Industrial Research (CSIR) India, for the support and permission to publish this article. The moral support and contribution of Mr. Pavan K. Srivastava at various levels is thankfully acknowledged. Thanks to Mr. Dharam Raj Yadav and other staff of the Building Materials Development Group AMPRI, Bhopal for their valued contribution. Authors are also grateful to CSIR, New Delhi, India for the valued support.

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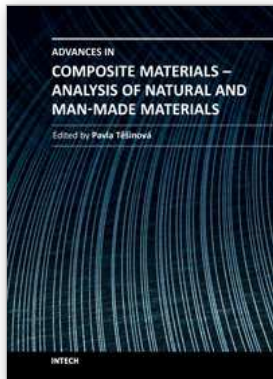
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## **Advances in Composite Materials - Analysis of Natural and Man-Made Materials**

Edited by Dr. Pavla Tesinova

ISBN 978-953-307-449-8

Hard cover, 572 pages

**Publisher** InTech

**Published online** 09, September, 2011

**Published in print edition** September, 2011

Composites are made up of constituent materials with high engineering potential. This potential is wide as wide is the variation of materials and structure constructions when new updates are invented every day. Technological advances in composite field are included in the equipment surrounding us daily; our lives are becoming safer, hand in hand with economical and ecological advantages. This book collects original studies concerning composite materials, their properties and testing from various points of view. Chapters are divided into groups according to their main aim. Material properties are described in innovative way either for standard components as glass, epoxy, carbon, etc. or biomaterials and natural sources materials as ramie, bone, wood, etc. Manufacturing processes are represented by moulding methods; lamination process includes monitoring during process. Innovative testing procedures are described in electrochemistry, pulse velocity, fracture toughness in macro-micro mechanical behaviour and more.

### **How to reference**

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Mohini Saxena, Asokan Pappu, Anusha Sharma, Ruhi Haque and Sonal Wankhede (2011). Composite Materials from Natural Resources: Recent Trends and Future Potentials, *Advances in Composite Materials - Analysis of Natural and Man-Made Materials*, Dr. Pavla Tesinova (Ed.), ISBN: 978-953-307-449-8, InTech, Available from: <http://www.intechopen.com/books/advances-in-composite-materials-analysis-of-natural-and-man-made-materials/composite-materials-from-natural-resources-recent-trends-and-future-potentials>

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