Chapter 1

1.0 INTRODUCTION

1.1 Overview of Composites

The advantage of composite materials over conventional materials stem largely from their higher specific strength, stiffness and fatigue characteristics, which enables structural design to be more versatile. By definition, composite materials consist of two or more constituents with physically separable phases. However, only when the composite phase materials have notably different physical properties it is recognized as being a composite material.

Composites are materials that comprise strong load carrying material (known as reinforcement) imbedded in weaker material (known as matrix). Over the last thirty years composite materials, plastics and ceramics have been the dominant emerging materials. The volume and number of applications of composite materials have grown steadily, penetrating and conquering new markets relentlessly. Modern composite materials constitute a significant proportion of the engineered materials market ranging from everyday products to sophisticated niche applications. While composites have already proven their worth as weight-saving materials, the current challenge is to make them cost effective. The efforts to produce economically attractive composite components have resulted in several innovative manufacturing techniques currently being used in the composites industry. [1]

It is obvious, especially for composites, that the improvement in manufacturing technology alone is not enough to overcome the cost hurdle. It is essential that there be an integrated effort in design, material, process, tooling, quality assurance, manufacturing, and even program management for composites to become competitive with metals. The composites industry has begun to recognize that the commercial applications of composites promise to offer much larger business opportunities than the aerospace sector due to the sheer size of transportation industry. Thus the shift of composite applications from aircraft to other commercial uses has become prominent in recent years. Increasingly enabled by the introduction of newer polymer resin matrix materials and high performance reinforcement fibers of glass, carbon and aramid, the penetration of these advanced materials has witnessed a
steady expansion in uses and volume. The increased volume has resulted in an expected reduction in costs. High performance FRP can now be found in such diverse applications as composite armoring designed to resist explosive impacts, fuel cylinders for natural gas vehicles, windmill blades, industrial drive shafts, support beams of highway bridges and even paper making rollers. For certain applications, the use of composites rather than metals has in fact resulted in savings of both cost and weight. Some examples are cascades for engines, curved fairing and fillets, replacements for welded metallic parts, cylinders, tubes, ducts, blade containment bands etc. Further, the need of composite for lighter construction materials and more seismic resistant structures has placed high emphasis on the use of new and advanced materials that not only decreases dead weight but also absorbs the shock & vibration through tailored microstructures. [1]

Composites are now extensively being used for rehabilitation/ strengthening of pre-existing structures that have to be retrofitted to make them seismic resistant, or to repair damage caused by seismic activity. Unlike conventional materials (e.g., steel), the properties of the composite material can be designed considering the structural aspects. The design of a structural component using composites involves both material and structural design.

Composite properties (e.g. stiffness, thermal expansion etc.) can be varied continuously over a broad range of values under the control of the designer. Careful selection of reinforcement type enables finished product characteristics to be tailored to almost any specific engineering requirement. Whilst the use of composites will be a clear choice in many instances, material selection in others will depend on factors such as working lifetime requirements, number of items to be produced (run length), complexity of product shape, possible savings in assembly costs and on the experience & skills the designer in tapping the optimum potential of composites. In some instances, best results may be achieved through the use of composites in conjunction with traditional materials.

1.2 Definition of Composite

A composite is a material system consisting of two or more phases on a macroscopic level, whose mechanical properties are designed to be superior to those of the constituent material acting independently. It is composed of two or more distinct phases. Matrix phase and reinforcing phase.
• **Matrix phase**

  The primary phase, having a continuous character, is called matrix. Matrix is more ductile and less hard phase. It holds the dispersed phase and shares a load with it.

• **Reinforcing phase**

  The second phase is embedded in the matrix in a discontinuous form. This secondary phase is called reinforcing phase. Dispersed phase is usually stronger than the matrix.

### 1.3 Classification of Composites

There are two classification systems of composite materials. One of them is based on the matrix material (metal, ceramic, polymer) and the second is based on the material structure[2].

- **Metal Matrix Composites (MMC)**

  Metal matrix composites are composed of a metallic matrix (aluminum, magnesium, iron, cobalt, copper) and a dispersed ceramic (oxides, carbides) or metallic (lead, tungsten, molybdenum) phase.

- **Ceramic Matrix Composites (CMC)**

  Ceramic matrix composites are composed of a ceramic matrix and embedded fibers of other ceramic material (dispersed or reinforcing phase).

- **Polymer Matrix Composites (PMC)**

  Polymer matrix composites are composed of matrix from thermoset (unsaturated polyester, epoxy) or thermoplastic (polycarbonate, polyvinyl chloride, nylon, polystyrene) polymers and embedded glass, carbon, aramid fibers (dispersed phase).

### 1.4 Types of Composites

Three types of composites are:

- Particle-reinforced composites
- Fiber-reinforced composites
- Structural Composites
  - Particle-reinforced composites

Particles used for reinforcing include ceramics and glasses such as small mineral particles, metal particles such as aluminum, and amorphous materials, including polymers and carbon black. Particles are used to:

- Increase the modulus of the matrix,
- Decrease the permeability of the matrix
- Decrease the ductility of the matrix.

Particles are also used to produce inexpensive composites. Reinforcers and matrices can be common, inexpensive materials and are easily processed. An example of particle reinforced composites is an automobile tyre which has carbon black particles in a matrix of polyisobutylene elastomeric polymer. Another example is spheroidized steel where cementite is transformed into a spherical shape which improves the machinability of the material. Another example for particle-reinforced composite is concrete where the aggregates (sand and gravel) are the particles and cement is the matrix. Particle reinforced composites support higher tensile, compressive and shear stresses.

- Fiber-reinforced composites

Reinforcing fibers can be made of metals, ceramics, glasses, or polymers that have been turned into graphite and known as carbon fibers. Fibers increase the modulus of the matrix material. The strong covalent bonds along the fiber’s length give them a very high modulus in this direction because to break or extend the fiber the bonds must also be broken or moved. Fibers are difficult to process into composites which makes fiber-reinforced composites relatively expensive. Fiber-reinforced composites are used in some of the most advanced, and therefore most expensive, sports equipment, such as a time-trial racing bicycle frame which consists of carbon fibers in a thermoset polymer matrix. Body parts of race cars and some automobiles are composites made of glass fibers (or fiberglass) in a thermoset matrix. [2]
The arrangement or orientation of the fibers relative to one another, the fiber concentration, and the distribution all have a significant influence on the strength and other properties of fiber-reinforced composites. Applications involving totally multidirectional applied stresses normally use discontinuous fibers, which are randomly oriented in the matrix material. Consideration of orientation and fiber length for particular composites depends on the level and nature of the applied stress as well as fabrication cost. Production rates for short-fiber composites (both aligned and randomly oriented) are rapid, and intricate shapes can be formed which are not possible with continuous fiber reinforcement.

### Structural Composites

The properties of structural composites depend on:

- Constituents
- Geometrical design

Common structural composite types are:

- Laminar: Is composed of two-dimensional sheets or panels that have a preferred high strength direction such as is found in wood and continuous and aligned fiber-reinforced plastics. The layers are stacked and cemented together such that the orientation of the high-strength direction varies with each successive layer. One example of a relatively complex structure is modern ski and another example is plywood.
- Sandwich Panels: Consist of two strong outer sheets which are called face sheets and may be made of aluminum alloys, fiber reinforced plastics, titanium alloys, steel. Face sheets carry most of the loading and stresses. Core may be a honeycomb structure which has less density than the face sheets and resists perpendicular stresses and provides shear rigidity. Sandwich panels can be used in variety of applications which include roofs, floors, walls of buildings and in aircraft, for wings, fuselage and tailplane skins.[1]

1.5 Characteristics of Composites

Properties of the composites are strongly influenced by the properties of their constituent materials, their distribution and interaction among themselves. Most important among them is volume or weight fraction. The contribution of a single constituent to the overall properties is determined by this parameter. If \( V_f \) total volume of the fiber and \( V_o \) is the total volume of the composite, then the fiber volume fraction is \( V_{fr} = V_f/V_o \).

The ratio of fiber to resin largely depends on the manufacturing processes used to combine them. However, it is influenced by the form which the fibers are incorporated. In general since the mechanical properties of fibers are higher than those of the resin, the higher the fiber volume fraction higher will be the mechanical properties of the resultant composite. The geometry of the fibers in a composite is also important as fibers have their highest mechanical properties along their length rather than across the widths. This leads to highly anisotropic properties of composites, where unlike metals the mechanical properties of composites are likely to be different in different directions. This means that it is very important while considering the composites, to understand at the design stage both magnitude and the direction of applied loads. When correctly accounted, these anisotropic properties can be very advantageous since it is only necessary to put material where loads will be applied and thus redundant material is avoided. Orientation of reinforcements affects the isotropy of the system, which determines the properties of the composite. Longitudinally aligned fibrous composites are inherently anisotropic, in this maximum strength and reinforcement are achieved along the direction of fiber alignment. In the transverse direction fiber reinforcement is virtually non-existent and fracture usually occurs at very low tensile stress, which may be less strength of the matrix. In randomly oriented composites strength lies between two extremes.
1.6 Classification of Fibers:

a) Natural Fibers
b) Synthetic Fibers

Fibers are class of hair-like materials that are in discrete elongated pieces, similar to pieces of thread. They can be spun into filaments, thread or rope. They can be used as a component of composite materials. Fiber can be classified into two main groups, which are man-made fiber and natural fiber. In general, natural fibers can be subdivided as to their origin such as plants, animals, or minerals; while man-made fibers can be subdivided to synthetic and natural polymers.

The first fibers used by man were natural fibers such as cotton, wool, silk, flax, hemp and sisal. The first man-made fiber was probably glass. Both natural and synthetic fibers (commonly known as man-made fibers) are now available and always being used as fillers in making a good properties of composites. The major fibers used till now can be classified into the groups given in Figure.

![Classification of Fibers](image)

Fig 1.2: Classification of Fibers
Reinforcing fibers in a single-layer composite may be short or long compared to its overall dimensions. The long fibers and short fibers are called continuous fibers and discontinuous fibers, respectively. The continuous fibers in a single-layer composite may be all aligned in one direction to form a unidirectional composite. The unidirectional composites are very strong in the fiber direction but are generally weak in the direction perpendicular to the fibers. The continuous reinforcement in a single layer may also be provided in a second direction to provide more balanced properties.

The bidirectional reinforcement may be provided in a single layer in mutually perpendicular directions as in a woven fabric. The orientation of short or discontinuous fibers cannot be easily controlled in a composite material. In most cases the fibers are assumed to be randomly oriented in the composite.

Alternatively, short fibers, sometimes referred to as chopped fiber may be converted to a lightly bonded perform or mat that can be later impregnated with resin to fabricate single-layer composites. Chopped fibers may also be blended with resins to make a reinforced molding compound. These fibers tend to become oriented parallel to the direction of material flow during a compression or injection molding operation and thus get a preferential orientation.

### 1.7 Synthetic fibers

Synthetic fibers are the result of extensive research by scientists to improve upon naturally occurring animal and plant fibers used in making cloth and rope. A large number of synthetic fibers with a variety of properties have been produced from polymers by various spinning techniques, including melt, dry, wet and emulsion spinning. Before synthetic fibers were developed, artificial (manufactured) fibers were made from cellulose, which comes from plants. At the beginning of the twentieth century, synthetic fibers started supplementing and replacing natural fibers. The first truly synthetic fiber was nylon, followed by polyesters, polyacrylics and polyolefins. Also synthetic elastomeric, glass and aramid fibers became important commercial products.[4]

Synthetic fibers are now available, ranging in properties from the high elongation and low-modulus elastomeric fibers, through the medium-elongation and medium-modulus fibers
such as polyamides and polyesters, to the low-elongation, high modulus carbon, aramid and inorganic fibers. With such a wide variety of synthetic fibers available, the volume of synthetic fibers consumed in worldwide is now greater than that of natural fibers. Most synthetic fibers have relatively smooth surfaces and they are frequently subjected to various mechanical and heat-setting processes to provide crimp. The modern synthetic fiber that was made from older artificial materials and become the most common of all reinforcing fibers for polymer matrix composites is glass fiber. Glass fiber is the dominant fiber and is used in 95% of cases to reinforce thermoplastic and thermoset composites. The principal advantages of glass fibers are low cost and high strength compared with others synthetic fibers. The disadvantages are low modulus and poor adhesion to polymer matrix resins, particularly in the presence of moisture. The classification of synthetic fibers is shown in Figure.

![Classification of Synthetic Fibers](Fig 1.3: Classification of Synthetic Fibers)
1.8 Natural Fibres

“Often when pursuing research into green composites we say we are protecting the environment that we are working for nature. We may as well stop kidding ourselves – nature will be fine; nature will work out OK and adapt to changes. It’s humans that will cease to exist if we continue the way we are at present. Some scientists and engineers have realized that they need to take responsibility for the outcome of their work. Researching ways of creating faster machines and bigger toys, without due consideration of the effects on the environment or on people, is irresponsible… We need to consider the impact that our material choice and design will have on the society and the environment”.

Generation of residues is inherent to human activities. After the Industrialization Period, with modernization of the society, the amount of industrial and postconsumer residues, together with the associated environmental problems, has been increasing at alarming levels. Residue management has become a major problem in modern society. The search for innovative solutions for the reuse of solid residues increased in the late 20th century and has intensified with growing urgency for environmental preservation. Many residue management solutions aim to add value to residue through the development of new materials and processes.

In recent years, there has been an increasing environmental consciousness and awareness of the need for sustainable development, which has raised interest in using natural fibres as reinforcements in polymer composites to replace synthetic fibres such as glass. [24] Natural fibers, as reinforcement, have recently attracted the attention of researchers because of their advantages over other established materials. They are environmentally friendly, fully biodegradable, abundantly available, renewable, cheap and have low density. Plant fibers are light compared to glass, carbon and aramid fibers. The biodegradability of plant fibers can contribute to a healthy ecosystem while their low cost and high performance fulfills the economic interest of industry. When natural fiber-reinforced plastics are subjected, at the end of their life cycle, to combustion process or landfill, the released amount of CO₂ of the fibers is neutral with respect to the assimilated amount during their growth. [17]

Polymeric materials reinforced with synthetic fibers such as glass, carbon and aramid provide advantages of high stiffness and strength to weight ratio as compared to conventional construction materials, i.e. wood, concrete and steel. In spite of these advantages, the
widespread use of synthetic fiber-reinforced polymer composite has a tendency to decline because of their high-initial costs and also production of synthetic composites requires a large quantum of energy and quality of environment suffered because of the pollution generated during the production and recycling of these synthetic materials.

In recent time plant fibers have been receiving considerable attention as substitutes for synthetic fiber reinforcements. Unlike the traditional synthetic fibers like glass and carbon these lignocellulosic fibers are able to impart certain benefits to the composites such as low density, high stiffness, low cost, renewability, biodegradability and high degree of flexibility during processing. Cellulosic fibers like sisal, coconut (coir) and bamboo in their natural form as well as several waste cellulosic products such as shell flour, wood flour and pulp have been used as reinforcing agents of different thermosetting and thermoplastic composites. [17]

- **Classification of Natural Fibres**

![Fig 1.4: Classification of Natural Fibres [14]](image-url)
1.9 Types of Natural Fibres

Natural fibers are subdivided based on their origins, for example vegetable/plants, animals, or minerals.

- Vegetable or Plant Based Natural Fibres-Extracted from Plants.
- Animal Fiber.
- Mineral fiber

1.9.1 Vegetable or Plant Based Natural Fibres-Extracted from Plants

Plant fibers are generally comprised mainly of cellulose: examples include cotton, jute, flax, ramie, sisal and hemp. Cellulose fibers serve in the manufacture of paper and cloth. This fiber can be further categorizes into following as: Seed fiber are the fibers collected from the seed and seed case e.g. cotton and kapok. Leaf fiber are the fibers collected from the leaves e.g. sisal and agave. Skin fiber are the fibers are collected from the skin or bast surrounding the stem of their respective plant.

These fibers have higher tensile strength than other fibers. Therefore, these fibers are used for durable yarn, fabric, packaging, and paper. Some examples are flax, jute, banana, hemp, and soybean. Fruit fiber are the fibers are collected from the fruit of the plant, e.g. coconut (coir) fiber. Stalk fiber are the fibers are actually the stalks of the plant. E.g. straws of wheat, rice, barley, and other crops including bamboo and grass. Tree wood is also such a fiber.

As aforementioned, with the increasing global energy crisis and ecology risk, plant-based fibre-reinforced polymer composites have attracted much interest owing to their potential of serving as alternatives for artificial fibre composites, like glass and carbon. Although the strength of such fibres (more than one type) are general lower than that of the traditional advanced composites, in certain extent, the strength of plant-based fibre-reinforced composites is sufficient enough for domestic or household plastic products.
Many attempts have been done in the past few years on using jute, bamboo, sisal, coir, hemp, flax, pineapple leaves, etc., for reinforcing different kinds of thermoplastic and thermoset polymers to form green composites. [6]

**Fig 1.5: Classification of Plant Fibers**

<table>
<thead>
<tr>
<th>Category</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seed fiber</td>
<td>Fibers collected from seeds or seed cases. e.g. cottonand kapok</td>
</tr>
<tr>
<td>Leaf fiber</td>
<td>Fibers collected from leaves. e.g. fique, sisal, banana, and agave.</td>
</tr>
<tr>
<td>Bast fiber</td>
<td>Fibers are collected from the skin or bast surrounding the stem of their respective plant. These fibers have higher tensile strength than other fibers. Therefore, these fibers are used for durable yarn, fabric, packaging, and paper. Some examples are flax, jute, kenaf, industrial hemp, ramie, rattan, and vine fibers.</td>
</tr>
<tr>
<td>Skin fiber</td>
<td>Fibers are collected from the fruit of the plant, e.g. coconut (coir) fiber.</td>
</tr>
<tr>
<td>Stalk fiber</td>
<td>Fibers are actually the stalks of the plant. E.g. straws of wheat, rice, barley, and other crops including bamboo and grass. Tree wood is also such a fiber.</td>
</tr>
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Table 1.1: Classification of Plant Based Fibres
• Some of Commonly Used Plant Based Natural Fibres

A. Sisal

The plants look like giant pineapples, and during harvest the leaves are cut as close to the ground as possible. The soft tissue is scraped from the fibres by hand or machine. The fibres are dried and brushes remove the remaining dirt, resulting in a clean fibre. Sisal produces sturdy and strong fibres. Sisal fibre is one of the prospective reinforcing materials that its use has been more experiential than technical until now. The use of 0.2% volume fraction of 25mm sisal fibres leads to free plastic shrinkage reduction. Sisal fibres conditioned in a sodium hydroxide solution retained respectively 72.7% and 60.9% of their initial strength after 420 days. As for the immersion of the fibres in a calcium hydroxide solution, it was noticed that original strength was completely lost after 300 days. According to those authors the explanation for the higher attack by Ca (OH) 2 can be related to a crystallization of lime in the fibres pores. Agave Sisalana Perrini is a native species to the Yucatan peninsula, and known worldwide, the plant and also the fibres, as Sisal, belonging to the class of natural hard fibres. [4]

Presently, Sisal represents the first natural fibre in commercial application, in which it is estimated in more than half of the total of all natural fibres used. The Sisal plant is a monocotyledonous, whose roots are fibrous, emerging from the base of pseudo stem. The fibres of Sisal are made of elementary fibres of 4 to 12 μm diameter that are aggregated by natural bound forming small cells of 1 to 2 μm. Such arrays are placed along the length of the plant on a regular shape, with lengths of 45 to 160 cm. The leaves of Sisal are an example of natural composite with lignocellulosic material presenting in 75 to 80 % of the total weight of the leaves, reinforced by helical micro fibres of cellulose, which represent about 9 to 12 % the total weight. The composition of Sisal fibre is basically of cellulose, lignin and hemicelluloses. [4]

The failure strength and the modulus of elasticity, besides the lengthening of rupture, depend on the amount of cellulose and the orientation of the micro-fibres. As a natural product these characteristics have a wide variation from one plant to another. The Sisal fibres are found commercially in several formats: fabric, cords, strips, wire, rolls, etc. [4]
Properties of this fibre are as follows: [4]

- Specific gravity [Kg/m³] 1370
- Water absorption [%] 110
- Tensile strength [M Pa] 347-378
- Modulus of elasticity [G Pa] 15

Available countries:
- East Africa, Bahamas, Antiqua, Kenya, Tanzania, India

Advantages

- They are very well resistant against moist.
- These fibres have a good tension resistance or tensile strength.
- They are very well resistant against heat.
- Sisal short fibres delay restrained plastic shrinkage controlling crack development at early ages.
- Sisal fibres conditioned in a sodium hydroxide solution retained respectively 72.7% and 60.9% of their initial strength.
• Disadvantages
  
a) decomposition in alkaline environments or in biological attack

• Applications
  
a) It is mainly used for ropes, mats, carpets and cement reinforcement.
  
b) It is also used cement reinforcement.
  
c) In developing countries, sisal fibres are used as reinforcement in houses.

B. Bamboo

Bamboo has been one of the common materials in pre-industrial architecture in Asia and South American countries, employed as structural elements. The utilization of bamboo as construction component is motivated by its widespread availability in the tropical and subtropical climatic regions, its rapid growth and the combination of elevated mechanical strength and low specific weight. However, at the present time, even the most modern construction where bamboo is used rely on a craft approach, with the know-how of construction techniques restricted to a small group of researchers, engineers and architects. Although bamboo has an immense potential, standardization and a definition of a correct construction practice still present some difficulties. Actually, there is an on-going research on bamboo with regards to special treatments leading to higher durability, improved connectors and mathematical modeling for the structural analysis of bamboo structures, along with the micro, macro- and nano-structural properties shutter bamboo concrete slabs, application of bamboo segments as reinforcement of concrete beams, circular columns and pillars in quadratic form of concrete, double-layer spatial and plane truss bamboo structure and special joints between the bamboo elements, which can be easily used for plane and double-layer spatial structures. It is now well established that bamboo is a composite material of cellulose fibres, with an average tensile resistance of about 700 MPa. These cellulose fibres are immersed in a lignin matrix. Studies showed that bamboo is a material with the variation of its physical and mechanical properties in an optimized form, according to the stresses generated due to wind load and its own weight. It has been observed on a macroscopic scale that the distances between the nodes (stiffeners), the diameter and the thickness vary along the total length of the bamboo Culm. The thickness, size and volumetric fraction of fibres vary,
becoming more concentrated as they approach the external shell. This is due to the higher forces applied to the external surface when the bamboo is subjected to bending by wind load.

The determination of how the variation of volumetric fracture occurs in the thickness is necessary for applying the theory of composite materials to bamboo, which allows the optimized use of bamboo on engineering sites. This variation of the properties as well as the macro, meso and microscopic characterize the graduate functionality of bamboo. There is ongoing research concerned with the structural analysis of bamboo frame structures commonly used by local people, improvement of the concrete permanent bamboo shutter slabs and reinforced concrete beams and columns, having in mind its improvement according to available knowledge. Fabrication of corrugated composite slabs based on cement paste reinforced with cellulose pulp of bamboo. The cement composites reinforced by bamboo pulps are produced by the vacuum pressure process, seeking to establish the characteristics of a material which can be easily fabricated, utilising the machinery of asbestos cement industry. The bamboo pulp is used in the paper industry on a large scale.

There are studies underway to produce durable furniture and new geometrical structural forms, as well as bicycles, tricycles and car bodies using bamboo. The first airplane which succeeded to fly was made with bamboo by the Brazilian Santos Dumont. [4]

- **Properties of this fibre are as follows:**

  Specific gravity [Kg/m3] 1158
  Water absorption [%] 145
  Tensile strength [MPa] 73-505
  Modulus of elasticity [GPa] 10-40

Available countries:-

India, Sri Lanka, Egypt, Guyana, Jamaica, Philippines, Malaysia
Advantages
   a) It has elevated mechanical strength.
   b) It has low specific weight too.
   c) It has high tensile strength.
   d) It has better modulus of elasticity than any other natural material.
   e) Easily and locally available material.

Disadvantages
   a) It is very much bad in torsion when it become mature.
   b) Probability of decomposition in biological attack.

Applications
   a) Bamboo segments are used as reinforcement of concrete beams, circular columns and pillars in quadratic form of concrete, double–layer spatial and plane truss bamboo structure and special joints between the bamboo elements, which can be easily used for plane and double-layer spatial structures.

   b) Bamboo frame structures commonly used by local people for improvement of the concrete permanent bamboo shutter slabs and reinforced concrete beams and columns.
C. Coir (Coconut Fibre)

Coconut fibre is obtained from the husk of the fruit of the coconut palm; the trees can grow up to 20 m, making harvesting a difficult job. People climb the tree to pick the nuts, or a pole with an attached knife is used. The fruits are dehusked with a spike and after retting, the fibres are extracted from the husk with beating and washing. The fibres are strong, light and easily withstand heat and salt water. After nine months of growth, the nuts are still green and contain white fibre, which can be used for the production of yarn, rope and fishing nets. After twelve months of growth, the fibres are brown and can be used for brushes and mattresses. The combined use of coconut and sisal short fibres seems to delayed restrained plastic shrinkage controlling crack development at early ages. Many aspects of the use of coir fibres as reinforcement in polymer–matrix composites are described in the literature. Coir is an abundant, versatile, renewable, cheap, and biodegradable lignocellulosic fibre used for making a wide variety of products. Coir has also been tested as a filler or a reinforcement in different composite materials. Furthermore, it represents an additional agro-industrial non-food feedstock (agro-industrial and food industry waste) that should be considered as feedstock for the formulation of ecocompatible composite materials. Coconut coir is the most interesting product as it has the lowest thermal conductivity and bulk density. The addition of coconut coir reduced the thermal conductivity of the composite specimens and yielded a lightweight product. Development of composite materials for buildings using natural fibre as coconut coir with low thermal conductivity is an interesting alternative which would solve environment and energy concern. Geethamma et al. have studied the dynamic mechanical behavior of natural rubber and its composites reinforced with short coir fibres. Coir fibre–polyester composites were tested as helmets, as roofing and postboxes.

These composites, with coir loading ranging from 9 to 15 wt%, have a flexural strength of about 38 MPa. Coir–polyester composites with untreated and treated coir fibres, and with fibre loading of 17 wt%, were tested in tension, flexure and notched Izod impact. The results obtained with the untreated fibres show clear signs of the presence of a weak interface long pulled-out fibres without any resin adhered to the fibres—and low mechanical properties were obtained. Although showing better mechanical performance, the composites with treated fibres present, however, only a moderate increase on the values of the mechanical properties analyzed. Alkali treatment is also reported for coir fibres. Treated fibre–polyester composites,
with volume fraction ranging from 10% to 30%, show better properties than composites with untreated fibres, but the flexural strength of these composites was consistently lower than that of the bare matrix. A maximum value of 42.3MPa is reported against a value of 48.5MPa for the neat polyester. Acetylation of coir fibres increases the hydrophobic behaviour, increases the resistance to fungi attack and also increases the tensile strength of coir–polyester composites. However, the fibre loading has to be fairly high, 45 wt% or even higher, to attain a significant reinforcing effect when the composite is tested in tension. Moreover, even with high coir fibre loading fractions, there is no improvement in the flexural strength. From these results, it is apparent that the usual fibre treatments reported so far did not significantly change the mechanical performance of coir–polyester composites.

Although there are several reports in the literature which discuss the mechanical behaviour of natural fibres reinforced polymer composites. However, very limited work has been done on effect of fibre length on mechanical behaviour of coir fibre reinforced epoxy composites. Against this background, the present research work has been undertaken, with an objective to explore the potential of coir fibre as a reinforcing material in polymer composites and to investigate its effect on the mechanical behaviour of the resulting composites. The present work thus aims to develop this new class of natural fibre based polymer composites with different fibre lengths and to analyse their mechanical behaviour by experimentation. [4]

- **Properties of this fibre are as follows:**

  Specific gravity [Kg/m3] 1177

  Water absorption [%] 93

  Tensile strength [MPa] 95-118

  Modulus of elasticity [GPa] 8

  Available countries:-

  India, Sri Lanka, Philippines, Malaysia
Advantages

a) The fibres are strong, light.
b) The fibres can easily withstand heat.
c) The fibres can withstand salt water.
d) The use of coconut fibres seem to delayed restrained plastic shrinkage controlling crack development at early ages.
e) Coir is an abundant, versatile, renewable, cheap, and lignocellulosic fibre.
f) The addition of coconut coir reduced the thermal conductivity of the composite specimens

Disadvantages

a) The fibres are biodegradable.

Applications

a) It is used for the production of yarn.
b) It is used for manufacture of rope and fishing nets.
c) It can be used for the production of brushes and mattresses.
d) Coir has also been tested as a filler or a reinforcement in different composite materials.
D. Jute

The fibres are extracted from the ribbon of the stem. When harvested the plants are cut near the ground with a sickle shaped knife. The small fibres, 5 mm, are obtained by successively retting in water, beating, stripping the fibre from the core and drying. A single jute fibre is a three dimensional composite composed mainly of cellulose, hemicelluloses, and lignin with minor amounts of protein, extractives and inorganics. These fibres were designed, after millions of years of evolution, to perform, in nature, in a wet environment. Nature is programmed to recycle jute, in a timely way, back to basic building blocks of carbon dioxide, and water through biological, thermal, aqueous, photochemical, chemical, and mechanical degradations.

In order to expand the use of jute fibre-based composites in adverse environments, it is necessary to interfere with nature's recycling chemistry. One of the most studied chemistries to interfere with nature's recycling chemistry and improve performance properties of jute fibre based composites involves reactions with acetic anhydride (acetylation). Chemical modifications of this type react with accessible hydroxyl groups on the cell wall polymers. These are the same hydroxyl groups involved in the natural degradation chemistries.

The addition of a simple acetate group on the natural fibre changes both rate and equilibrium properties. Lignocellulosic fibres are favorably bonded with phenolic resin to have better water resistance rather than urea or melamine resin. Hence, water soluble phenol formaldehyde resin was selected for the development of rigid jute board for good serviceable mechanical properties. To achieve better wet ability of jute with resin and to improve strength properties, fibre pre-treatment is necessary. Simple pre-treatment is done with low-condensed resins like melamine resin, phenolic resin and CNSL modified phenol formaldehyde resin.

Jute as other lignocellulosic fibres consists of –OH group which causes it susceptible to moisture and directly impairs the properties of jute composite specially dimensional stability. Due to this polar group, jute also is not efficiently adhered to non polar matrices. To overcome this difficulties this fibre should be modified chemically or hydrothermally. To improve the interface adhesion between the non polar matrices and hydrophilic fibre, coupling agent or compatibiliser should be used. Some investigations were done by cyanoethylation and acetylation of jute fibre to reduce the –OH content. The both processes are effective for
dimensional stability. Cyanoethylation also improves the bonding between jute and non polar matrix like unsaturated polyester resin. [4]

Fig 1.9: Jute Fibre Plant& Jute-fibre-hanging-out-to-dry-in-the-sun

- **Properties of the fibre are as follows:**
  
  Specific gravity [kg/m3] 1460
  Water absorption [%] 13
  Tensile strength [MPa] 400-800
  Stiffness [KN/mm2] 10-30

  Available countries:-
  India, Egypt, Guyana, Jamaica, Ghana, Malawi, Sudan, Tanzania

- **Advantages**
  
  a) It can withstand rotting very easily.
  b) Lignocellulosic fibres are favorably bonded with phenolic resin to have better water resistance.
  c) The fibres can easily withstand heat.
  d) It has high tensile strength.

- **Disadvantages**
  
  a) Due to its short fibre length, Jute is the weakest stem fibre than other fibres.
  b) Jute fibre based composites involve reactions with acetic anhydride (acetylation).
  c) The fibres are biodegradable.
• **Applications**
  
  *a*) It is used as packaging material (bags).
  
  *b*) It is used as carpet backing, ropes, yarns.
  
  *c*) It is used for wall decoration.
1.9.2 Animal Fiber

Animal fiber generally comprise proteins; examples mohair, wool, silk, alpaca, angora. Animal hair (wool or hair) are the fibers taken from animals or hairy mammals. E.g. Sheep’s wool, goat hair (cashmere, mohair), alpaca hair, horse hair, etc. Silk fiber are the fibers collected from dried saliva of bugs or insects during the preparation of cocoons. Examples include silk from silk worms. Avian fiber are the fibers from birds, e.g. feathers and feather fiber.

- Some of Commonly Used Animal Based Natural Fibres

  A. Silk-based fibre

  Apart from the plant-based fibres, animal-based fibres become other alternatives for producing biodegradable, biomedical and bio-resorbable composite materials for
bioengineering and orthopaedic applications. The content of these fibres are mainly made by proteins, like wool, spider and silkworm silk. The enhanced environmental stability of silk fibres in comparison to globular proteins is due to the extensive hydrogen bonding, the hydrophobic nature of much of the protein, and the significant crystallinity. Silk proteins—known as silk fibroins are stored in the glands of insects and spiders as an aqueous solution. During the spinning process, silkworm accelerates and decelerates its head in arcs to each change of direction, and the concentration of silk in the solution is gradually increased and finally, elongation stress is applied to produce a partly crystalline, insoluble fibrous thread in which the bulk of the polymer chains in the crystalline regions are oriented parallel to the fibre axis. Faster spinning speed leads to stronger but more brittle fibres where slower speed leads to weaker and more extensible fibres. At even greater speed, silk toughness decreased, mainly due to the loss of extensibility. [6]

![Fig. 1.11. Raw Cocoon silks (a) and side view of the silk fibre (b).](image)

Cocoons are natural polymeric composite shells made of a single continuous silk strand with length in the range of 1000–1500 m and conglutinated by sericin. This protein layer resists oxidation, is antibacterial, ultra-violet (UV) resistant, and absorbs and releases moisture easily. Since this protein layer can be cross-linked, copolymerized, and blended with other macromolecular materials, especially artificial polymers, to produce materials with improved properties. In average, the cocoon production is about 1 million tonnes worldwide, and this is equivalent to 400,000 tonnes of dry cocoon.
In the tissue engineering area, silks have been identified as a kind of biomaterials, used for healing process for bone, tendons or ligament repairs. Slowly degrading biomaterials which can maintain tissue integrity following implantation, while continually transferring the load-bearing burden to the developing biological functional tissue are desired. In such phenomena, the gradual transfer of the load-bearing burden to the developing and/or remodelling tissue should support the restoration and maintenance of tissue function over the life of the patient. [6]

Silk fibre spun out from silkworm cocoons are consisted of fibroin in the inner layer and sericin in the outer layer, all are protein based. From outside to inside layers of cocoon, the volume fractions of sericin decreases while the relative content of fibroin increases. Also, it is known that silk fibroin consists of both hydrophilic and hydrophobic regions which is a block-like polymeric system. These fibres have a highly non-uniform cross-sectional geometry with respect to both shape and absolute dimensions. By changing the reeling conditions, silkworm silk can be stronger, stiffer and more extensible, approaching to the properties of spider dragline silk. Each raw silk thread has a lengthwise striation, consisting of two separate but irregularly entwined fibroin filaments embedded in sericin. Silk sericin is a minor protein that envelops silk fibroin fibre and glues them together to form cocoon shape. Fibroin and sericin in silk account for about 75 and 25 wt%, respectively. Silk fibre is biodegradable and highly crystalline with a well-aligned structure. Composition, structure and material properties of silk fibre produced by spiders, silkworms, scorpions, mites and flies may differ widely depending on the specific source and the uncontrollable reeling conditions of those insects. Spinning under controlled conditions will have more uniform cross-sectional area of silk fibre, reproducible molecular alignment and fewer micro-structural flaws. The size and weight of cocoons decrease with an increase in temperature and cocoons can bear efficiently both external static forces and dynamic impact loadings.

Normal compact cocoon exhibits a high ability of elastic deformation with an elastic strain limit higher than 20% in both longitudinal and transverse directions. Anisotropic properties mainly due to the non-uniform distribution and orientations of silk segments and the inner layer of cocoon has low porosity (higher silk density) and smaller average diameter of silk, therefore, there is an increase in elastic modulus and strength from outside to inside layers. That is, the thinner the silk, the higher the elastic modulus and tensile strength and the
maximum values at the innermost layer. On the other hand, temperature above the glass
transition temperature, the cocoon and its layers become softer and softer and behave similar
to a rubber-like material. Silk fibre have higher tensile strength than glass fibre or synthetic
organic fibre, good elasticity, and excellent resilience. They resist failure in compression,
stable at physiological temperatures and sericin coating is water-soluble proteinaceous glue.
Fibroin is a semi-crystalline polymer of natural fibrous protein mainly consists of two phases:
namely β-sheet crystals and non-crystalline including micro-voids and amorphous structure,
by which the structure of sericin coating is amorphous acting as an adhesive binder to
maintain the fibroin core and the overall structural integrity of the cocoon. Degumming is a
key process during which sericin is removed by thermo-chemical treatment of the cocoon.
Although this surface modification can affect the tensile behavior and the mechanical
properties of silk significantly, it is normally done to enhance interfacial adhesion between
fibre and matrix. [6]

In addition, according to Altman, silks are insoluble in most solvents, including water,
dilute acid and alkali. Reactivity of silk fibre with chemical agents is positively correlated to
the largeness of internal and external surface areas. When fabricating silk-based composites,
the amount of resin gained by fibre is strongly related to the degree of swelling of the non-
crystalline regions, that is, the amorphous regions and the micro-voids inside the fibre.

B. Chicken feather fibre

Chicken feather fibre (CFF) has attracted much attention to different product design
and engineering industries recently, so as the use of CFF as reinforcements for polymer-based
biodegradable materials has emerged gradually. The advantages of using this natural fibre
over traditional reinforcing fibres in biocomposites are low cost, low density, acceptable
specific strength, recyclability, bio-degradability etc. CFF, because of its renewable and
recyclable characteristics, have been appreciated as a new class of reinforcements for
polymer-based biocomposites. However, the full understanding of their mechanical properties,
surface morphologies, environmental influences due to moisture and chemical attacks,
bonding characteristics between silk fibroin and surrounding matrix and manufacturing
process is essential. According to the survey conducted recently, a chicken processing plant
produces about 4000 pounds of chicken feathers every hour.
In most western countries, these feathers are used as (i) feather fibre feed; (ii) air filter elements that replaces traditional wood pulps (retarding the trees cut down rate) and (iii) lightweight feather composites. Chicken feathers are approximately 91% protein (keratin), 1% lipids, and 8% water. The amino acid sequence of a chicken feather is very similar to that of other feathers and also has a great deal in common with reptilian keratins from claws. The sequence is largely composed of cystine, glycine, proline, and serine, and contains almost no histidine, lysine, or methionine. In fact, a CFF is made up of two parts, the fibres and the quills (see Fig.). The fibre is thin filamentous materials that merge from the middle core material called quills. In simple terms, the quill is hard, central axis off which soft, interlocking fibres branch. Smaller feathers have a greater proportion of fibre, which has a higher aspect ratio than the quill.

Fig. 1.12. A typical chicken feather fibre. [4]

The presence of quill among fibres results in a more granular, lightweight, and bulky material. A typical quill has dimensions on the order of centimeters (length) by millimeters (diameter). Fibre diameters were found to be in the range of 5–50 lm. The density of CFF is lighter than other synthetic and natural reinforcements, thus, CFF inclusion in a composite could potentially lower composite density, whereas the den- sity of a typical composite with
synthetic reinforcing increases as fibre content increases. Hence, light weight composite materials can be produced by inclusion of CFF to plastics which even reduces the transportation cost. The barbs at the upper portion of the feather are firm, compact, and closely knit, while those at the lower portion are downy, i.e. soft, loose, and fluffy.

The down feather provides insulation, and the flight feather provides an airfoil, protects the body from moisture, the skin from injury, and colors and shapes for displays. Fig. shows the cross-sectional views of the flight and down feather fibres. It is obvious that flight feather fibre exited in a hollow form while down fibre is in solid. In terms of the purpose of fibre-reinforcement, the use of down fibre appears much better than that the use of flight fibre. The moisture content of CFF is an important factor that can highly influence their weight and mechanical properties. The moisture content of processed CFFs can vary depending upon processing and environmental conditions. The glass transition temperature (Tg) of the feather fibres and inner quills is approximately 235°C while an outer quills is 225°C. High Tg represents that a tighter keratin structure is formed to which water is more strongly bonded. Fibres and inner quills do not begin to lose water below 100°C.

The moisture evolution temperature of the CFF and quill occurs in the range of 100–110°C. This suggests that it may be possible to have a fully dry fibres and inner quills at 110°C. The length and diameter (sometime in the form of bundles) of CFF would highly affect their properties and impregnatability of resin into a resultant composite. Therefore, the control of resin temperature (thus, its viscosity), while at the same time to manage the sonication (ultrasonic vibration) time to facilitate the resin penetration rate into the fibres are essential. Short or longer fibres would highly affect the stress transferability as well as shear strength of the composites.

The fibres, themselves also would be a barrier to the movement of polymer chains inside the composites and it may result in increasing their strength and thermal properties, but reduce their fracture toughness. These properties will be studied in detail, in this project. Fig. 1.12 shows the SEM image of the down chicken feather fibre and its strength compared with other type of feathers. It was found that the development of chicken feather fibre biocomposites have been increasing in recent years, and the outcome are expected to be able to alleviate the global waste problem.
1.9.3 Mineral fiber

Mineral fibers are naturally occurring fiber or slightly modified fiber procured from minerals. These can be categorized into the following categories: Asbestos is the only naturally occurring mineral fiber. Variations are serpentine and amphiboles, anthophyllite. Ceramic fibers includes glass fibers (Glass wood and Quartz), aluminium oxide, silicon carbide, and boron carbide. Metal fibers includes aluminium fibers.

<table>
<thead>
<tr>
<th>Fiber Type</th>
<th>Country</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flax</td>
<td>Borneo, China</td>
</tr>
<tr>
<td>Hemp</td>
<td>Yugoslavia, China</td>
</tr>
<tr>
<td>Sun Hemp</td>
<td>Nigeria, Guyana, Siera Leone, India</td>
</tr>
<tr>
<td>Ramie</td>
<td>Honduras, Mauritius</td>
</tr>
<tr>
<td>Jute</td>
<td>India, Egypt, Guyana, Jamaica, Ghana, Malawi, Sudan, Tanzania</td>
</tr>
<tr>
<td>Kenaf</td>
<td>Iraq, Tanzania, Jamaica, South Africa, Cuba, Togo</td>
</tr>
<tr>
<td>Roselle</td>
<td>Borneo, Guyana, Malaysia, Sri Lanka, Togo, Indonesia, Tanzania</td>
</tr>
<tr>
<td>Sisal</td>
<td>East Africa, Bahamas, Antiqua, Kenya, Tanzania, India</td>
</tr>
<tr>
<td>Abaca</td>
<td>Malaysia, Uganda, Philippines, Bolivia</td>
</tr>
<tr>
<td>Coir</td>
<td>India, Sri Lanka, Philippines, Malaysia</td>
</tr>
</tbody>
</table>

Table 1.2: Fibers and countries of origin

1.10 Properties of Natural Fibres:

<table>
<thead>
<tr>
<th>Natural Fibres</th>
<th>Tensile strength (MPa)</th>
<th>Elongation at break (%)</th>
<th>Young modulus (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flax</td>
<td>300–1500</td>
<td>1.3–10</td>
<td>24–80</td>
</tr>
<tr>
<td>Jute</td>
<td>200–800</td>
<td>1.16–8</td>
<td>10–55</td>
</tr>
<tr>
<td>Sisal</td>
<td>80–840</td>
<td>2–25</td>
<td>9–38</td>
</tr>
<tr>
<td>Kenaf</td>
<td>295–1191</td>
<td>3.5</td>
<td>2.86</td>
</tr>
<tr>
<td>Pineapple</td>
<td>170–1627</td>
<td>2.4</td>
<td>60–82</td>
</tr>
<tr>
<td>Banana</td>
<td>529–914</td>
<td>3</td>
<td>27–32</td>
</tr>
<tr>
<td>Coir</td>
<td>106–175</td>
<td>14.21–49</td>
<td>4–6</td>
</tr>
<tr>
<td>Oil palm (empty fruit)</td>
<td>130–248</td>
<td>9.7–14</td>
<td>3.58</td>
</tr>
<tr>
<td>Oil palm (fruit)</td>
<td>80</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>Ramie</td>
<td>348–938</td>
<td>1.2–8</td>
<td>44–128</td>
</tr>
<tr>
<td>Hemp</td>
<td>310–900</td>
<td>1.6–6</td>
<td>30–70</td>
</tr>
<tr>
<td>Wool</td>
<td>120–174</td>
<td>25–35</td>
<td>2.3–3.4</td>
</tr>
<tr>
<td>Spider silk</td>
<td>875–972</td>
<td>17–18</td>
<td>11–13</td>
</tr>
<tr>
<td>Cotton</td>
<td>264–800</td>
<td>3–8</td>
<td>5–12.6</td>
</tr>
</tbody>
</table>

Table 1.3: Mechanical properties of different types of potential natural fibres [6]
- **Comparison of Natural Fibres with Glass Fibre**

<table>
<thead>
<tr>
<th>Properties</th>
<th>E-glass</th>
<th>flax</th>
<th>hemp</th>
<th>jute</th>
<th>ramie</th>
<th>coir</th>
<th>sisal</th>
<th>abaca</th>
<th>cotton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density g/cm³</td>
<td>2.55</td>
<td>1.48</td>
<td>1.46</td>
<td>1.5</td>
<td>1.25</td>
<td>1.33</td>
<td>1.5</td>
<td>1.51</td>
<td></td>
</tr>
<tr>
<td>Tensile strength* 10E⁶ N/m²</td>
<td>2400</td>
<td>800 - 1500</td>
<td>550 - 900</td>
<td>400 - 800</td>
<td>500</td>
<td>220</td>
<td>600-700</td>
<td>980</td>
<td>400</td>
</tr>
<tr>
<td>E-modulus (GPa)</td>
<td>73</td>
<td>60 - 80</td>
<td>70</td>
<td>10 - 30</td>
<td>44</td>
<td>6</td>
<td>38</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Specific (E/density)</td>
<td>29</td>
<td>26 - 46</td>
<td>47</td>
<td>7 - 21</td>
<td>29</td>
<td>5</td>
<td>29</td>
<td>8</td>
<td></td>
</tr>
<tr>
<td>Elongation at failure (%)</td>
<td>3</td>
<td>1.2 - 1.6</td>
<td>1.6</td>
<td>1.8</td>
<td>2</td>
<td>15 - 25</td>
<td>2 - 3</td>
<td>3 - 10</td>
<td></td>
</tr>
<tr>
<td>Moisture absorption (%)</td>
<td>-</td>
<td>7</td>
<td>8</td>
<td>12</td>
<td>12 - 17</td>
<td>10</td>
<td>11</td>
<td>8 - 25</td>
<td></td>
</tr>
<tr>
<td>price/Kg ($), raw (mat/fabric)</td>
<td>1.3 (1.7/3.8)</td>
<td>0.6 - 1.5 (2/4)</td>
<td>0.35 (1.5/0.9 (2/4))</td>
<td>1.5 - 2.5</td>
<td>0.25 - 0.5</td>
<td>0.6 - 0.7</td>
<td>1.5 - 2.5</td>
<td>1.5 - 2.2</td>
<td></td>
</tr>
</tbody>
</table>

Table 1.4: Material and mechanical properties of E-glass and other plant-based fibres. [6]

<table>
<thead>
<tr>
<th>Properties</th>
<th>Flax</th>
<th>Hemp</th>
<th>Jute</th>
<th>Kenaf (Bast)</th>
<th>E-Glass Fibre</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single fibre length (mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Range</td>
<td>10-70</td>
<td>7-55</td>
<td>2-5</td>
<td>1.4-5</td>
<td>–</td>
</tr>
<tr>
<td>Average</td>
<td>32</td>
<td>25</td>
<td>20</td>
<td>21</td>
<td>2.6</td>
</tr>
<tr>
<td>Bundle fibre length (mm)</td>
<td>250-1200</td>
<td>1000-4000</td>
<td>1500-3600</td>
<td>1500-4000</td>
<td>–</td>
</tr>
<tr>
<td>Mean diameter (μm)</td>
<td>19</td>
<td>25</td>
<td>20</td>
<td>21</td>
<td>–</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>1.4</td>
<td>1.48</td>
<td>1.46</td>
<td>1.2</td>
<td>2.55</td>
</tr>
<tr>
<td>Moisture absorption (%)</td>
<td>7</td>
<td>8</td>
<td>12</td>
<td>12</td>
<td>–</td>
</tr>
<tr>
<td>Tensile strength (N/m²)</td>
<td>800-1500</td>
<td>550-900</td>
<td>400-800</td>
<td>275-450</td>
<td>2400</td>
</tr>
<tr>
<td>Young’s modulus, E (GPa)</td>
<td>60-80</td>
<td>70</td>
<td>10-30</td>
<td>–</td>
<td>73</td>
</tr>
<tr>
<td>Specific E/density</td>
<td>26-46</td>
<td>47</td>
<td>7-21</td>
<td>–</td>
<td>29</td>
</tr>
<tr>
<td>Elongation at break (%)</td>
<td>1.2-1.6</td>
<td>1.6</td>
<td>1.8</td>
<td>–</td>
<td>3</td>
</tr>
<tr>
<td>Cellulose (%)</td>
<td>78.5</td>
<td>68.1</td>
<td>58-63</td>
<td>60.8</td>
<td>–</td>
</tr>
<tr>
<td>Hemi-cellulose (%)</td>
<td>9.2</td>
<td>15.1</td>
<td>21-24</td>
<td>20.3</td>
<td>–</td>
</tr>
<tr>
<td>Lignin (%)</td>
<td>8.5</td>
<td>10.6</td>
<td>12-14</td>
<td>11.0</td>
<td>–</td>
</tr>
<tr>
<td>Pectin (%)</td>
<td>2.3</td>
<td>3.6</td>
<td>#</td>
<td>3.2</td>
<td>–</td>
</tr>
<tr>
<td>Ash (%)</td>
<td>1.5</td>
<td>2.5</td>
<td>0.5</td>
<td>4.7</td>
<td>–</td>
</tr>
</tbody>
</table>

*No authoritative value available.

Note: Properties of natural fibres vary and depend upon the fibre preparation, test specimen, testing method, origin of fibres, agricultural parameters, and so on.

Table 1.5: Physical, mechanical and chemical properties of bast fibres
1.11 Advantages of Natural Fibres

+ Low specific weight, which results in a higher specific strength and stiffness than glass. This is a benefit especially in parts designed for bending stiffness.
+ It is a renewable resource, the production requires little energy, CO\textsubscript{2} is used while oxygen is given back to the environment.
+ Producible with low investment at low cost, which makes the material an interesting product for low-wage countries.
+ Friendly processing, no wear of tooling, no skin irritation
+ Thermal recycling is possible, where glass causes problems in combustion furnaces.
+ Good thermal and acoustic insulating properties

1.12 Disadvantages of Natural Fibres

− Lower strength properties, particularly its impact strength
− Variable quality, depending on unpredictable influences such as weather.
− Moisture absorption, which causes swelling of the fibres
− Restricted maximum processing temperature.
− Lower durability, fibre treatments can improve this considerably.
− Poor fire resistance
− Price can fluctuate by harvest results or agricultural politics

1.13 Applications of Natural Fibres:

Composites currently occupy many market sectors of which a number are suited to the introduction of natural fibre composites as an alternative. Currently, the largest areas in which natural fibre composites are being employed include the automotive and construction industries.

Fibre quality for high end applications is often proportional to cost, for example the strongest flax fibre is slightly more expensive than glass due to competition with the textile industry, but lower grades of flax from linseed oil production are less expensive.

The relative costs of other natural fibres such as jute, coir, sisal, hemp are considerably lower than glass, and vary with proximity to market and various agronomic factors between
regions. Production costs are reported to be reduced by 10-30% when natural fibres are used in place of glass fibre. The use of conventional processing methods means there is no need for new processing equipment and the equivalent processing conditions make transfer to this alternative feedstock very simple. Natural fibres are a good candidate fibre to use in products where traditionally glass fibres have been used. It is estimated that there are some 2.3 million tonnes of glass fibres being used in various applications around the globe, so there are a number of opportunities for natural fibres to be used in place of existing glass fibres. Natural fibres have several advantages over glass fibre: low density, low cost, high toughness, acceptable specific strength properties, good thermal properties, low embodied energy, reduced tool wear reduced tool wear in the moulding process and have better acoustic properties thereby reducing cabin noise, reduced irritation to the skin and respiratory system, and they also have a low energy requirement for processing. In addition they are biodegradable or recyclable depending on the selected matrix.

The biodegradable polymer matrices are still considerably higher priced than the “big four” thermoplastics (PE, PP, PS and PVC), although the costs have in general fallen during the last ten years as industrial production has scaled up. The costs are now roughly equivalent with the costs of more specialist polymers such as polycarbonate. If we address a few of the main industrial sectors highlighted above we can see what has been showcased as the most recent developments in these sectors. [27]

![Fig 1.13: Application of Natural Fibres](image-url)
1.13.1 Automotive Industry

Current well-established applications of natural fibres in automotive vehicles. The schematic of a generic vehicle, Table 5, shows current applications from a range of different manufacturers. The type of natural fibre selected for manufacture is influenced by the proximity to the source of fibre, thus panels from India and Asia contain jute, ramie and kenaf, panels produced in Europe tend to use flax or hemp fibres, panels from South America tend to use sisal, curaua, and ramie.

The typical weight of natural fibres used within various parts of a vehicle are shown in Table: Virtually all of the major car manufacturers in Germany (i.e., Daimler-Chrysler, Mercedes, Volkswagen Audi Group, BMW, Ford and Opel) now use natural fibre composites in

<table>
<thead>
<tr>
<th>AUTOMOTIVE MANUFACTURER</th>
<th>MODEL APPLICATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>AUDI</td>
<td>A2, A3, A4 (Avant), A6, A8, Roadster, Coupe</td>
</tr>
<tr>
<td></td>
<td>Seat backs, side and back door panels, boot lining, hat rack, spare tyre lining</td>
</tr>
<tr>
<td>BMW</td>
<td>3, 5, 7 series</td>
</tr>
<tr>
<td></td>
<td>Door panels, headliner panel, boot lining, seat backs, noise insulation panels, moulded footwell linings</td>
</tr>
<tr>
<td>CITROEN</td>
<td>C5</td>
</tr>
<tr>
<td></td>
<td>Interior door paneling</td>
</tr>
<tr>
<td>DAIMLER-CHRYSLER</td>
<td>A, C, E and S-class models, Evolus (exterior)</td>
</tr>
<tr>
<td></td>
<td>Door panels, windshield, dashboard, business table, pillar cover panel</td>
</tr>
<tr>
<td>FIAT</td>
<td>Punto, Brava, Marea, Alfa romeo 146, 156</td>
</tr>
<tr>
<td>FORD</td>
<td>Mondeo CD 162, Focus</td>
</tr>
<tr>
<td></td>
<td>Door panels, B-pillar, boot liner</td>
</tr>
<tr>
<td>LOTUS</td>
<td>Eco Elise (July 2008)</td>
</tr>
<tr>
<td></td>
<td>Body panels, B-pillar, Interior carpets</td>
</tr>
<tr>
<td>MERCEDES-BENZ</td>
<td>TRUCKS</td>
</tr>
<tr>
<td></td>
<td>Internal engine cover, engine insulation, sun visor, interior insulation, bumper, wheel box, roof cover</td>
</tr>
<tr>
<td>PEUGEOT</td>
<td>406</td>
</tr>
<tr>
<td></td>
<td>Seat backs, parcel shelf</td>
</tr>
<tr>
<td>RENAULT</td>
<td>Clio, Twingo</td>
</tr>
<tr>
<td></td>
<td>Rear parcel shelf</td>
</tr>
<tr>
<td>ROVER</td>
<td>2000 and others</td>
</tr>
<tr>
<td></td>
<td>Insulation, rear storage shelf/panel</td>
</tr>
<tr>
<td>SAAB</td>
<td>Door panels</td>
</tr>
<tr>
<td>SEAT</td>
<td>Door panels, seat backs</td>
</tr>
<tr>
<td>TOYOTA</td>
<td>Avensis, Harrier, Celsior, Raum</td>
</tr>
<tr>
<td></td>
<td>Door panels, seat backs, Spare tyre cover</td>
</tr>
<tr>
<td>VAUXHALL</td>
<td>Corsa, Astra, Vectra, Zafira</td>
</tr>
<tr>
<td></td>
<td>Headliner panel, interior door panels, pillar cover panel, instrument panel</td>
</tr>
<tr>
<td>VOLKSWAGEN</td>
<td>Golf, Passat, Bora</td>
</tr>
<tr>
<td></td>
<td>Door panel, seat back, boot lid finish panel, boot liner</td>
</tr>
<tr>
<td>VOLVO</td>
<td>C70, V70</td>
</tr>
<tr>
<td></td>
<td>Seat padding, natural foams, cargo floor tray</td>
</tr>
</tbody>
</table>

Table 1.6. Vehicle manufacturers and use of natural fibre composites. [27]
applications such as those listed in Table 1.6. Ford uses from 5 to 13 kg (these weights include wool and cotton)22. The car manufacturer, BMW, has been using natural materials since the early 1990’s in the 3, 5 and 7 series models with up to 24kg of renewable materials being utilised.

In 2001, BMW used 4,000 tonnes of Natural fibres in the 3 series alone. Here the combination is a 80% flax with 20% sisal blend for increased strength and impact resistance. The main application is in interior door linings and panelling. Wood fibres are also used to enclose the rear side of seat backrests and cotton fibres are utilized as a sound proofing material.

![Components on a generic vehicle, made from natural fibre composite materials](image)

Fig 1.14. Components on a generic vehicle, made from natural fibre composite materials [27]

<table>
<thead>
<tr>
<th>Applications</th>
<th>Fiber</th>
<th>Size of Opportunity</th>
<th>Key Drivers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Door panel/inserts</td>
<td>Kenaf/ Hemp</td>
<td>Medium</td>
<td>• Lighter weight</td>
</tr>
<tr>
<td></td>
<td>Wood fiber</td>
<td></td>
<td>• Lower cost</td>
</tr>
<tr>
<td>Rear parcel shelves</td>
<td>Kenaf Flax</td>
<td>Medium</td>
<td>• Eco friendly</td>
</tr>
<tr>
<td>Seatbacks</td>
<td>Flax</td>
<td>Medium</td>
<td>• Governmental support</td>
</tr>
<tr>
<td>Spare tyre covers</td>
<td>Flax</td>
<td>Medium</td>
<td>• Friendly processing</td>
</tr>
<tr>
<td>Other interior trim</td>
<td>Kenaf Flax</td>
<td>Small</td>
<td>• Thermal recycling is possible</td>
</tr>
<tr>
<td>Spare-wheel pan</td>
<td>Abaca</td>
<td>Medium</td>
<td>• Good thermal and acoustic insulating properties</td>
</tr>
</tbody>
</table>

Table 1.7: Application of Natural Fibres in Automotive Industry
In 2000, Audi launched the A2 mid-range car which was the first mass-produced vehicle with an all-aluminium body. To supplement the weight reduction afforded by the all-aluminium body, door trim panels were made of polyurethane reinforced with a mixed flax/sisal mat. This resulted in extremely low mass per unit volume and the panels also exhibited high dimensional stability.

Recently, in the last few years, Volvo have started to use Soya based foam fillings in their seats along with natural fibres. They have also produced a cellulose based cargo floor tray – replacing the traditional flax and polyester combination used previously which resulted in improved noise reduction. [27]

<table>
<thead>
<tr>
<th>Component</th>
<th>Weight (Kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Front door liners</td>
<td>1.2-1.8</td>
</tr>
<tr>
<td>Rear door liners</td>
<td>0.8-1.5</td>
</tr>
<tr>
<td>Boot liners</td>
<td>1.5-2.5</td>
</tr>
<tr>
<td>Parcel Shelves</td>
<td>&lt;2</td>
</tr>
<tr>
<td>Seat Backs</td>
<td>1.6-2</td>
</tr>
<tr>
<td>Sunroof shields</td>
<td>&lt;0.4</td>
</tr>
<tr>
<td>Headrests</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Table 1.8. Natural fibre usage per component [27]

The two most important factors now driving the use of natural fibres by the automotive industry are cost and weight, but ease of vehicle component recycling is also an ever increasing consideration to meet the requirements of the end of life vehicle directive. When you consider that 10million cars are scrapped in Europe each year (11m in the US), and of those 96% are processed by shredder facilities, leaving 25% of the vehicles weight remaining as waste products in the form of plastics, fibres, foams, glass and rubber. The directive aims to ‘depollute’ all scrapped vehicles, avoid hazardous waste and reduce the amount of materials going to landfill sites to a maximum of 5% per car by 2015.
• Racing Cars

The ethos for the Eco-1 racing car (Figure 1.15) was simple: ‘Create a high-performance racing car that had a conscience’. Wherever possible, sustainable materials and manufacturing processes were used during construction. Eco-1 has tyres, bodywork, brake pads, lubricants and fuel made from natural, renewable materials. The chassis is made from steel and aluminium which can be recycled easily and efficiently. The tyres have a component which is made from Potato or maize starch and are commercially available road legal tyres that offer very low rolling resistance. The hydraulic oil and the engine oil are a plant oil ester (which can also be used in a standard road car). The brake pads are made from CNSL (Cashew Nut Shell Liquid), Hemp and Jute, and the fuel to power the vehicle is derived from wheat. In total the racing car is 90-95% recyclable or biodegradable. Just because the materials the car is made from are friendly to the environment, it doesn’t mean that performance has to be compromised. It is a car with a power-to-weight ratio of 350bhp per tonne, a car that does 0-62mph in four seconds, and that will go on to a top speed in excess of 125mph.

Fig. 1.15. Eco-1 racing car [25]

1.13.2 Construction Industry

The construction industry constitutes the second largest sector to employ natural materials in a range of products which include (but are not limited to):

1. Light structural walls
2. Insulation materials
3. Floor and wall coverings
4. Geotextiles
5. Thatch Roofing

We are also seeing a range of products such as sisal cement products – roof tiles and building blocks being produced in countries such as Tanzania and Brazil. Coir based products from India, which are strong, naturally termite and insect resistant, waterproof, flame resistant and carpenter friendly (excellent nail and screw holding properties) which make them ideal candidate materials in the construction sector.

<table>
<thead>
<tr>
<th>Applications</th>
<th>Fiber</th>
<th>Size of Opportunity</th>
<th>Key Drivers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decking</td>
<td>Wood, Flax, Rice husk, Bagasse</td>
<td>High</td>
<td>• Lower life cycle cost</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Low &amp; easy maintenance</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Low moisture absorption</td>
</tr>
<tr>
<td>Railing Systems</td>
<td>Wood, Flax, Rice husk, Bagasse</td>
<td>High</td>
<td>• Lower variability than wood</td>
</tr>
<tr>
<td>Window frame</td>
<td>Wood, Flax, Rice husk, Bagasse</td>
<td>High</td>
<td>• Eco friendly</td>
</tr>
<tr>
<td>Fencing</td>
<td>Wood, Flax, Rice husk, Bagasse</td>
<td>Medium</td>
<td>• Governmental regulations</td>
</tr>
<tr>
<td>Panels</td>
<td>Wood, Flax, Rice husk, Bagasse, coir, stalk</td>
<td>High</td>
<td></td>
</tr>
</tbody>
</table>

Table 1.9: Application of Natural Fibres in Construction

1.13.3 Leisure Industry

A range of products for the leisure industry have been publicised recently incorporating natural fibres. This section identifies just a few of these products.

- **Fishing Rods**

Cellucomp have developed a fishing rod based on carrot fibres. The material is trademarked as CURRAN and is made from a high strength biofibre. The fibre used is nanoscopic in size which not only provides incredible strength, stiffness and toughness but also allows for a very smooth surface finish in the final product. The fibres have a stiffness of 130GPa, strength of upto 5GPa and failure strains of over 5%. The CURRAN material can also be utilised in a range of other sports equipment such as snowboards. The new “Just Cast” rods are around 50 per cent carrot - each made with around 2kg of the vegetables. But it is
hoped that as the technique is developed, they will eventually be able to make products which are made from 100 per cent biological matter - carrots and other plants.

Through a special process, nano fibres found in carrots are extracted and combined with high-tech resins enabling tough, durable components to be moulded to whatever shape, degree of stiffness, strength or lightness required. The company are already looking at using other vegetables such as turnips, swede and parsnips for other applications. It is interesting to note that carrots were one of the candidate materials considered by Henry Ford back in the early 1930’s for use in vehicle body parts. [27]

- **Audio Components**

Eureka project E! 2819- Factory Ecoplast is combining natural fibres with thermoplastics to create new recyclable compounds for consumer products and audio components. Partners in the Eureka Factory Ecoplast project decided to join efforts to develop a palletized compound suitable for injection moulding and extrusion processes, combining two or more material components in such a way that the resulting compound is better than any of the individual components alone.

The new materials are suitable for use in the manufacture of a wide variety of products, including vacuum cleaner and lawn mower parts, storage boxes and even golf tees. Further tests of the project’s new ‘Eureka’ speaker boxes show higher frequency acoustic performance on a par with market leaders.

- **Bicycles**

The Museeuw bicycle incorporates flax fibres along with carbon fibres to produce the ‘flax carbon hybrid race bike’. This bicycle was designed and built by the former world cycling champion Johan Museeuw. The bikes (3 different designs) are manufactured by hand and provide a unique combination of exceptional stiffness and tremendous absorption, providing a very pleasing ride (according to users) without any additional weight. Future developments include creating a wheel from 50% flax and 50% carbon fibre. [27]
1.13.4 Miscellaneous Products

Included in this category are items such as grinding wheel discs with 1 million units being produced each year under the trade name Plantex, in this instance hemp and polypropylene (PP) are being used to create the backing plates for these industrial products.

Cosmetic packaging is an area also seeing the adoption of natural fibres. In the USA, a lip stick casing made from Flax fibres and PP which has been on sale for 4 years selling 4 million units per year. Funeral Urns made from natural fibres and PLA which after a limited time will naturally decompose leaving no physical residue behind.

Key events such as the 2008 Olympics hosted by China and held in Beijing (predominantly) presented an ideal opportunity to utilise natural materials on a global stage. This event alone used 80,000 tonnes of natural fibres, mainly in the buildings.

- **NF composites, state-of-the-art**

  In the past two decades, growing interest for NF 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, resulting in applications shown in figure 1.16. Experiences from NF composite applications in western countries can be applied in developing new products, suitable for agro-industrial countries. In the following section possible applications are discussed. [12]

![Fig. 1.16: A flax –reinforced car roof](image1) ![A flax –reinforced catamaran hull](image2)
- **Roofing panels**

  Natural fibres and resin material can be pressed into laminates that can act as skins of so called sandwiches (layered panel consisting of skins and a core), see figure 1.17. Rural societies these panels can be used as roofing, see figure 1.17. Compared to corrugated iron roofing the natural fibre sandwich has improved thermal and acoustic insulating properties and doesn’t cause zinc and rust pollution. Due to the use of local resources, the natural fibre sandwich is probably cheaper to manufacture. In comparison with traditional vegetable roofing, the sandwich is more durable. Similar panels can also be used as doors, tabletops and shelves.

![Fig. 1.17: Two natural fibre sandwiches. Left: foam core. Right: bamboo core](image1)

![Fig. 1.18: Various roofing constructions. Top left: Corrugated iron roof. Top right: Traditional vegetable roof. Bottom: Natural fibre sandwich roof. [12](image2)
• Fluid container

Using cost effective filament winding equipment, see figure 1.19, reusable containers (figure 4.7) for transport and storage of liquids (water, beer, wine, fish- and soy-sauce) can be filament wound, from spun natural fibres. Using natural rubber as resin, the container becomes “foldable-when-empty”. The thermal properties of the natural fibres keep the contents cool. The advantage over plastic or steel vessels is the environmental friendly design, the low weight and the reduction in transport- and manufacturing costs. [12]

Fig. 1.19: Cost-effective filament winder & Manufacturing of a Sisal storage container

• Constructive bridge parts

Using pultrusion technology, natural fibre construction profiles can be manufactured at any length, see figure 1.20. A very useful application of these profiles in combination with the panels described earlier is a simple pedestrian bridge, see figure 1.20. This bridge is easily transported to remote locations due to its lightweight and withstands tropical conditions better than metal bridges. Due to the low weight, a less complicated foundation is required. Also window- or doorframes, scaffoldings and tubes can be made. [12]
Fig. 1.20: Pultruded Sisal profile  Bridge suitable for composite application[12]

- **Small boats**

  Small canoe-like boats, see figure 1.21, can be manufactured with vacuum techniques. These boats withstand corrosion better than metal boats and the low weight makes them easy to handle, both in the water and ashore. In addition, they are more durable than steel, wooden or bamboo boats. [12]

Fig. 1.21: Composite canoe from Botswana
### Availability of Natural Fibre in India and its Applications in Building Materials

<table>
<thead>
<tr>
<th>Item</th>
<th>Source</th>
<th>Qty. in Mt/Yr.</th>
<th>Application in Building Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rice Husk</td>
<td>Rice mills</td>
<td>20</td>
<td>As fuel, for manufacturing building materials and products for production of rice husk binder, fibrous building panels, bricks, acid proof cement</td>
</tr>
<tr>
<td>Banana leaves/stalk</td>
<td>Banana plants</td>
<td>0.20</td>
<td>In the manufacture of building boards, fire resistance fibre board</td>
</tr>
<tr>
<td>Coconut husk</td>
<td>Coir fibre industry</td>
<td>1.60</td>
<td>In the manufacture of building boards, roofing sheets, insulation boards, building panels, as a lightweight aggregate, coir fibre reinforced composite, cement board, geo-textile, rubberized coir</td>
</tr>
<tr>
<td>Groundnut shell</td>
<td>Groundnut oil mills</td>
<td>11.00</td>
<td>In the manufacture of buildings panels, building blocks, for making chip boards, roofing sheets, particle boards</td>
</tr>
<tr>
<td>Jute fibre</td>
<td>Jute Industry</td>
<td>1.44</td>
<td>For making chip boards, roofing sheets, door shutters</td>
</tr>
<tr>
<td>Rice/wheat straw</td>
<td>Agricultural farm</td>
<td>12.00</td>
<td>Manufacture of roofing units and walls panels/boards</td>
</tr>
<tr>
<td>Saw mill waste</td>
<td>Saw mills/wood</td>
<td>2.00</td>
<td>Manufacture of cement bonded wood chips, blocks, boards, particle boards, insulation boards, briquettes</td>
</tr>
<tr>
<td>Sisal fibres</td>
<td>Sisal plantation</td>
<td>0.023 (Asia)</td>
<td>For plastering of walls and for making roofing sheets, composite board with rice husk, cement roofing sheet, roofing tiles, manufacturing of paper and pulp</td>
</tr>
<tr>
<td>Cotton stalk</td>
<td>Cotton plantation</td>
<td>1.10</td>
<td>Fibre boards, panel, door shutters, roofing sheets, autoclaved cement composite.</td>
</tr>
</tbody>
</table>

Table 1.10: Availability of Natural Fibre in India and its Applications in Building Materials
1.14 Cost of Fibers

The cost of the cellulose fibers is also a factor that could influence fiber selection. Fiber prices tend to fluctuate considerably and are dependent on a number of factors, such as supply and demand, quality and exchange rates. A comparison of the relative costs of a number of fibers can be seen in Table 1.11.

<table>
<thead>
<tr>
<th>Fiber Type</th>
<th>Price Us$ / Kg</th>
<th>Price Rs / Kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jute</td>
<td>0.3 – 0.7</td>
<td>15 – 75</td>
</tr>
<tr>
<td>Hemp</td>
<td>0.5-1</td>
<td>25- 50</td>
</tr>
<tr>
<td>Flax</td>
<td>0.4-0.8</td>
<td>20 - 40</td>
</tr>
<tr>
<td>Sisal</td>
<td>0.4-1</td>
<td>20 -50</td>
</tr>
<tr>
<td>Wood</td>
<td>0.2-0.4</td>
<td>10 - 20</td>
</tr>
<tr>
<td>Glass</td>
<td>1.5-3.2</td>
<td>75 - 160</td>
</tr>
<tr>
<td>Carbon</td>
<td>10-200</td>
<td>500 – 10,000</td>
</tr>
</tbody>
</table>

Table 1.11: Natural Fiber Costs

The costs of bulk cellulose fibers are considerably lower than those of glass and carbon, but cellulose fibers require further processing to get them into a form where they can be used in composites. Despite this, cellulose fibers still appear to be a cheaper option when compared to synthetic fibers.

From the information it can be seen that the strongest cellulose fibers are hemp, jute and flax, with hemp and flax having the highest values for Young’s modulus. Hemp and flax fibers also have high aspect ratios (length/width), which is a desirable attribute for fibers to be used as Composite reinforcement.

The most suitable cellulose fibers for use in composite materials are therefore hemp and flax. Flax is more widely accessible and slightly cheaper than hemp due to its widespread use in the textiles industry. Hemp, however, has the potential for much higher fiber yields that could result in lower costs with improvements in cultivation techniques. Hemp, compared to flax, also has the advantage of being extremely disease and pest resistant, and can be planted at high densities to prevent weeds from growing between the plants. Pesticides and herbicides
are therefore not required in the cultivation of hemp, and this provides a distinct advantage over flax in many countries where restrictions on herbicide use is prevalent.

1.15 Natural Resins:

- Natural Resins
  - Damar
  - Mastic
  - Copal

Nowadays, resins are classified into Natural Resin and Synthetic resin. Natural resins are produced from some kind of trees. Damer, Mastic and Copal are known as typical natural resin for painting materials. Synthetic resin was developed in 20th century. Acrylic, Vinyl and Alqid resin are known as typical synthetic resin. In this page, I describe about mostly natural resin.

Natural resins are classified into Soft resin such as Dammer or Mastic, and Hard resin such as Copal or Amber. Soft resin dissolves into Turpentine easily. The layer included soft resin have good glossy. On the other hand Hard resin doesn't dissolve into Turpentine. It's a little difficult to make it be a varnish. However the layer included hard resin is extremely strong and have good endurance against humidity.

**Damar**

Dammar or Damar is A Soft Living Resin gathered from trees in tropical Asia such as Malaysia or Indonesia. The island of Sumatera in Indonesia is known as a place of production of the best dammer for Art material. This resin is called Sumatera Damar. Damers has been used by European painters since 19th century. The property is similar to Mastic, but Damar varnish doesn't make Blooming Phenomenon ( Mastic varnish sometimes makes foggy effect on the surface of canvas in the high humidity and temperature ).

![Fig. 1.22: Damar](image)
Painters dissolve Damars into Turpentine to make damar varnish. Usually, the ratio is 1 Dammar into 2 or 3 Turpentine. Pure Turpentine dissolves Dammars well, but Petroleum solvents sometimes can't dissolve them perfectly. For homemade, I recommend Turpentine as compare with Petroleum’s.

Damar varnish can be used as Protect vernish, Retouching varnish, Ingredient for painting mediums or tempera mediums, etc. For Protect vernish, 1 Damar and 3 Turpentine is recommended. The film of damar varnish as protect layer can be rediscover by solvents. So, when the film become yellow or dark, you can remove it and paint new film. For Retouching varnish, 1 Damar and 5 Turpentine. For Ingredient for painting mediums, 1 Damar and 2 Turpentine is recommended. Dammer Varnish provides grassy and transparency to films. And Painters can dissolve Damars into Drying oil by Heating. Damars melt around 90 degrees centigrade.

- **Mastic**

  Mastic is A Soft Living Resin gathered from trees in islands of Mediterranean sea. The island of Chios is known as a place of production of the best Mastic resin for art use. This resin is called Chios Mastic. Mastic is much more expensive than Damer. And Mastic varnish sometimes makes foggy effect on the surface of canvas in the high humidity and temperature. The film tend to yellowing and cracking with age. Therefore Mastic was almost replaced by Damar in the 20th century.

- **Copal**

  Copal is A Hard Semi-fossil resin (Some are Living resin) gathered from fossil or living trees. Copal doesn't dissolve in Terpentine or Petroleum solvents (only Manira copal dissolve into alcohol). Copals melt at high temperature. It depend on the hardness of each copals. E.g. Manila copal melts 250 or 260 degrees centigrade.
1.16 Types of Natural Resins, Sources, Properties and Uses:

<table>
<thead>
<tr>
<th>Resin</th>
<th>Source/type</th>
<th>Melting point (°C)</th>
<th>Density</th>
<th>Ref. Index</th>
<th>Acid number</th>
<th>Saponification number</th>
<th>Solubility</th>
<th>Characteristics</th>
<th>Uses</th>
</tr>
</thead>
<tbody>
<tr>
<td>amber</td>
<td>fossil resins</td>
<td>150-225</td>
<td>1.05-1.1</td>
<td>1.54 - 1.55</td>
<td>15-30</td>
<td>115-225</td>
<td>Amber is very resistant to acids and alkalis and is not entirely soluble in any solvent</td>
<td>yellowish, hard, glassy, fossil resin; Mohs hardness = 2.5-3.0; Succinates emit succinic acid when heated; fluoresces a strong yellowish green to bluish white in short-wave UV light</td>
<td>varnishes for coaches, locomotives, oilcloth, amber substitute</td>
</tr>
<tr>
<td>copal</td>
<td>Euphorbiaceae resins from Trachycarpus species (Africa), Hymenaea courbaril (South America) and Agathis australis (New Zealand)</td>
<td>180-340</td>
<td>1.04-1.1</td>
<td>1.32-1.54</td>
<td>122-128</td>
<td>132-178</td>
<td>After melting, copals are soluble in oil and turpentine. Soft copals are partially soluble in ethanol, chloroform, glacial acetic acid,</td>
<td>May fluoresce white in short-wave UV</td>
<td>varnishes for coaches, locomotives, oilcloth, amber substitute</td>
</tr>
<tr>
<td>dammar</td>
<td>Diterpenes resin from southeast Asia of the genera Shorea, Balanocarpus, or Hopea</td>
<td>90 (sphenes); 100-180 (melts); Tg = 39.3</td>
<td>1.04-1.12</td>
<td>1.515 - 1.539</td>
<td>16-18</td>
<td>20-65</td>
<td>Soluble in turpentine, oil, chloroform and aromatic hydrocarbons</td>
<td>Darkens with age. Turns cloudy when moisture is present during preparation</td>
<td>picture varnish, printing ink, mounting thin sections, alkali baking enamels, paper and textile coatings</td>
</tr>
<tr>
<td>elemi</td>
<td>from trees of the family Bursarineae</td>
<td>77-121</td>
<td>1.17-2.5</td>
<td>1.17-2.5</td>
<td>23-50</td>
<td></td>
<td>Soft, sticky, odoriferous resin</td>
<td>Soft, sticky, odoriferous in oil media; printing ink, cheving gum</td>
<td>plasticizing additive in varnishes; lithographic inks, paper and textile coatings, perfume bases, waterproofing</td>
</tr>
<tr>
<td>mastic</td>
<td>from myrrh shrub, Pistacia lentiscus, in southern Europe and northern Africa</td>
<td>95-120; Tg = 34.7</td>
<td>1.074</td>
<td>1.525 - 1.536</td>
<td>50-71</td>
<td>82-92</td>
<td>Soluble in oil, turpentine, ethanol, diethyl ether, benzene, acetone, chloroform</td>
<td>Darkens and becomes less soluble with age. May turn cloudy if moisture is present during preparation</td>
<td>picture varnish, additive in oil media; printing ink, cheving gum</td>
</tr>
<tr>
<td>resin</td>
<td>from Coniferae trees (longleaf pine (Pinus palustris), Cuban pine (P. caribaea), loblolly pine (P. taeda), cluster pine (P. pinaster), or Scotch pine (P. sylvestris))</td>
<td>100-150</td>
<td>1.07-1.1</td>
<td>1.525 - 1.548</td>
<td>150-180</td>
<td>150-200</td>
<td>Soluble in ethanol, acetone, turpentine, acetic acid, carbon disulfide</td>
<td>Oxidizes easily and may blacken with age. Combustible, burning with a yellow, sooty flame</td>
<td>paints, varnishes, inks, adhesives, sealing wax, soldering fluxes, and limelite. Also used to increase sliding friction on musical instrument bows and dance floors</td>
</tr>
<tr>
<td>sandarac</td>
<td>From the alera tree Calitris quadrivalvis native to Australia and the sandarac tree Tetracris articulata native to northern Africa</td>
<td>125-150</td>
<td>1.07-1.0</td>
<td>1.545</td>
<td>140-155</td>
<td>143</td>
<td>Soluble in ethanol, ether, acetone, amyl alcohol and hot alkali</td>
<td>Brittle</td>
<td>spirit and oil varnishes</td>
</tr>
<tr>
<td>shellac</td>
<td>excreted by the female of the lac insect, Lacca laca, native to India</td>
<td>115-120</td>
<td>1.035 - 1.140</td>
<td>1.316</td>
<td>48-64</td>
<td>185-213</td>
<td>Fresh shellac is soluble in ethanol, acetone. Shellac becomes insoluble with age</td>
<td>Shellac number = 10-18; unbleached shellac will autoflourish orange; moisture can produce a white haze on dried surface</td>
<td>furniture polishes, protective coatings for cluster molds, composition products; gramophone records</td>
</tr>
</tbody>
</table>

Table 1.12: Properties of Natural Fibres
1.17 Matrix

The role of matrix in a fiber-reinforced composite is to transfer stress between the fibers, to provide a barrier against an adverse environment and to protect the surface of the fibers from mechanical abrasion. The matrix plays a major role in the tensile load carrying capacity of a composite structure. The binding agent or matrix in the composite is of critical importance. Four major types of matrices have been reported: Polymeric, Metallic, Ceramic and Carbon. Most of the composites used in the industry today are based on polymer matrices. Polymer resins have been divided broadly into two categories: Thermosetting and Thermoplastics.

1.18 Polymeric Materials

Few polymers are thermally stable by comparison with metals or ceramics and even the most stable, like the polyamides, or polyether ether ketone (known as PEEK) are degraded by exposure to temperatures above about 300°C. There is nothing that reinforcement can do to combat chemical degradation, but the associated fall in strength and increase in time-dependent (creep or visco-elastic) deformation, a feature common to all polymers, though less serious in cross-linked resin systems than in thermoplastics, can be delayed by fiber reinforcement.[39]

1.18.1 Thermoset Polymers

They undergo a chemical change by the action of heating, a catalyst, or ultraviolet light. They are hardened into a permanent shape that CANNOT be altered by reapplying heat or catalysts. Thermosets are NOT weldable, but they can be repaired with flexible parts repair materials. Thermoset materials are generally stronger than thermoplastic materials due to this three dimensional network of bonds (cross-linking), and are also better suited to high-temperature applications up to the decomposition temperature. However, they are more brittle. Many thermosetting polymers are difficult to recycle.

Most commonly used thermo set polymers are epoxy resins, Unsaturated Polyester resins (as in fiberglass), Vinyl Ester, Phenolic Epoxy, Novolac and Polyamide. Unsaturated
polyesters are extremely versatile in properties and applications and have been a popular thermo set used as the polymer matrix in composites. They are widely produced industrially as they possess many advantages compared to other thermosetting resins including room temperature cure capability, good mechanical properties and transparency. The reinforcement of polyesters with cellulosic fibers has been widely reported. Polyester-jute Polyester-sisal, polyester-coir polyester-banana-cotton, polyester-straw, polyester-pineapple leaf, and polyester- cotton-kapok, are some of the promising systems.

- **Examples of Thermosets are given below**

**Polyester** Fiber glass systems: sheet molding compounds and bulk molding compounds

- **Vulcanized rubber**
- **Bakelite, a phenol-formaldehyde** resin used in electrical insulators and plastic ware
- **Duroplast**, light but strong material, similar to bakelite used for making car parts
- **Urea-formaldehyde** foam used in plywood, particleboard and medium-density fiberboard
- **Melamine** resin used on worktop surfaces
- **Epoxy** resin used as the matrix component in many fiber reinforced plastics such as glass reinforced plastic and graphite-reinforced plastic
- **Polyimides** used in printed circuit boards and in body parts of modern airplanes
- **Cyanate esters or polycyanurates** for electronics applications with high demands on dielectric properties and high glass temperature requirements in composites
- **Mold or mold runners** (the black plastic part in integrated circuits or semiconductors)
- **High density polyethylene (HDPE)**
- **Low density polyethylene (LDPE)**
- **Chlorinated polyethylene (CPE)**
- **Polypropylene (PP)**
- **Normal polystyrene (PS)**
- **Poly (Vinyl chloride) PVC**
- **Mixtures of polymers**
- **Recycled Thermoplastics**
1.18.1.1 Unsaturated Polyester Resins (UPR)

UPR is one of the widely used thermosets especially in the industrial application and mostly being reinforced with fibers or fillers. Hence, this study is an attempt of using natural fiber as reinforcing filler, replacing synthetic fiber which is more commonly used, using readily available UPR as the matrix. Coconut coir, chosen as the natural cellulose filler, which belongs to the biomass materials abundantly available in India and other countries. However, in producing a good lignocellulosic composite, the main obstacle to be resolved is the compatibility between the filler and the matrix. The properties of the lignocellulosic composites are dominated by the interfacial interaction between the lignocellulosic filler and polymer matrix.

The unsaturated polyester resin is a Thermoset resin was defined as a plastic material which was initially a liquid monomer or oligomers or a pre-polymer, which was cured by either application of heat or catalyst to become an infusible and insoluble material. Thermoset polymers have covalent bonds linking the polymer chains in three dimensions. These links prevent the chains from sliding past one another resulting in a higher modulus and improved creep resistance. Usually thermosets were more brittle than thermoplastics.

The polymer chains in thermosets were below their glass transition at room temperature, making them glassy. Among the most common thermosetting resins used in composite manufacturing were unsaturated polyesters, epoxies, vinyl esters, amino resin and phenolics. In this research, unsaturated polyester resin was preferred due to their good range of mechanical properties, relatively low cost, corrosion resistance and low molecular weight. Therefore, polyesters were suitable for a variety of applications and are adaptable to the fabrication of large structures.

The unsaturated polyester resin is a low-viscosity thermoset polymer. It is especially suitable for hand lay-up (HLU) and resin transfer moulding (RTM) due to its low viscosity and non-thixotropic nature.
• **Curing of Unsaturated Polyester Resin**

The curing agent used was cobalt octate as accelerator and methyl-ethyl-ketone peroxide (MEKP) as catalyst. Used 0.03/2.0 weight ratio respectively. The cobalt accelerator was a solution of cobalt salts diluted in styrene and white spirit of 12% (w/w) cobalt content, which was mixed into the resin first, before the MEKP catalyst.

The catalyst was a solution of MEKP diluted in dibutyl phthalate of 50% (w/w) MEKP content. This cure system was chosen to allow cure to occur in a reasonable time, in order to allow sheets of resin to be moulded before gelation occurs. To determine reactivity, a pre-mixed resin (0.03 g accelerator/2 g MEKP and 100 g resin) was poured into a thermoset cup and allowed to react from an initial mould temperature of 25 °C. Chemical activity of the resin system during its transition from liquid to a solid was monitored to determine the gelation time 27 minutes. [41]

• **Typical Properties of Unsaturated Polyester Resin**

Tensile stress and strain at failure of the neat resin was found 63 MPa and 4.7% respectively. Fracture toughness, KIc, and fracture energy, Glc, obtained for the polyester resin lie between the typical values for epoxy resins and polystyrene, which was found 0.30 MPa m^{0.5} and 90 J/m2 respectively. Flexural stress and flexural strain at failure of the Resin was found 78 MPa and 1.8% respectively.

The Resin used in this work has the following properties (provided by the manufacturer.)

- Manufacturer name: Ashland India Pvt. Ltd.
- Product name: AROPOL IN 1005P,
- Brook field viscosity: cPs--- 318,
- Acid value: MgKOH/gm---21.16,
- Gel time at 25°C----12.0 minutes,
- Non volatile matter-------62.08%,
- Peak exotherm temperature------187°C,
- Mixing ratio for 100gm of resin is 1%cobalt 3.0gm and MEKP 1.5gm.
1.18.2 Thermoplastics:

Thermoplastics are polymers that require heat to make them process able. After cooling, such materials retain their shape. In addition, these polymers may be reheated and reformed, often without significant changes in their properties. The thermoplastics which have been used as matrix for natural fiber reinforced composites are as follows:

Only those thermoplastics which are useable for natural fiber reinforced composites, and processing temperature (temperature at which fiber is incorporated into polymer matrix) does not exceed 230°C. These are, most of all, poly olefins, like polyethylene and polypropylene. Technical thermoplastics, like polyamides, polyesters and polycarbonates require processing temperatures > 250°C and are therefore not useable for such composite processing without fiber degradation.

<table>
<thead>
<tr>
<th>Thermosets:</th>
<th>Symbol</th>
<th>crystallinity</th>
<th>Glass transition Temp - (T_g), °C</th>
<th>Max use Temp - °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyester</td>
<td>PE</td>
<td>no</td>
<td>80</td>
<td>100-50</td>
</tr>
<tr>
<td>Epoxy</td>
<td>Ep</td>
<td>no</td>
<td>120-180</td>
<td>150</td>
</tr>
<tr>
<td>Phenolic</td>
<td>Ph</td>
<td>no</td>
<td>130-180</td>
<td>200</td>
</tr>
<tr>
<td>Bismaleimide</td>
<td>BMI</td>
<td>no</td>
<td>180-200</td>
<td>220</td>
</tr>
<tr>
<td>Polylimide</td>
<td>PI</td>
<td>no</td>
<td>300-330</td>
<td>280</td>
</tr>
</tbody>
</table>

**Thermoplastics:**

| Polyamide (Nylon) | PA     | yes           | 80                              | 125             |
| Polyphenylene sulphone | PPS | yes           | 100                              | 260             |
| Poly(ether ether etone) | PEEK | yes           | 143                              | 250             |
| Polycarbonate     | PC     | no            | 145                              | 125             |
| Polysulphone      | PS     | no            | 190                              | 150             |
| Polyetherimide    | PEI    | no            | 210                              | 170             |
| Polyether sulphone | PES | no            | 230                              | 180             |
| Thermoplastic polyimide | TPI | no            | 270                              | 240             |

Table 1.13: Thermal Stability of Some Matrix Polymers
1.19 Natural Fibre-Polymer Composites

Polymer matrix composites using natural plant fibres as reinforcement has attracted a lot of interest in recent years. The main reasons are that these natural fibres can be harvested from renewable resources, possess long aspect ratio for efficient stress transfer, and certain aspects of their mechanical properties are comparable to existing inorganic glass fibres. With these plant fibres, sisal, jute, flax, hemp, banana and coconut have attracted particular attention.

1.20 Fabrication of Fiber Reinforced Thermoplastic Composites

The processing methods used to fabricate natural fiber reinforced thermoplastic composites are generally the same as those used to produce similar composites containing synthetic fibers. The most commonly used techniques for mixing fibers with a thermoplastic polymer are melt mixing and extrusion. Injection moulding and compression moulding are the two most commonly used composite forming techniques, although extrusion is used in some instances. No serious attempts have yet been made to develop large-scale fabrication techniques for natural fiber reinforced thermoplastic composites with aligned fiber orientations

- Melt Mixing

Melt mixing using a radial flow (turbulent) mixer is a commonly used method in the scientific literature for compounding short reinforcing fibers with thermoplastic polymers. The thermoplastic polymer is initially heated to its melting temperature, and then reinforcing fibers are added to the mix. After mixing has taken place the composite mix can be rolled or formed into the desired shape. Various mixer settings, such as the mixing duration, rotor speed and melt-chamber temperature can affect the composite properties. Joseph et al. combined sisal fibers with polypropylene using a Haake Rheocord mixer. They showed that ineffective mixing and poor fiber dispersion occurred at short mixing times (<10 min) and low mixing speeds (<50 rpm), while low mixing temperatures (<170°C) resulted in extensive fiber breakages. Composite strength losses due to fiber breakage also occurred at high mixing times (>10 min) and high mixing speeds (>50 rpm), with high mixing temperatures resulting in fiber degradation and poor fiber dispersion. Melt mixing generally results in very good mixing of the fibers with the thermoplastic polymer, but is a non-continuous process that only
allows the processing of a limited amount of material at any given time, and requires stoppages to remove the material from the mixer. Melt mixing can only be used as a means of mixing the material, and further processing is required to fashion the material into its desired shape and form.

- **Extrusion Compounding**

  Despite the numerous studies on retting, physical modification and chemical modification, there are only a limited number of investigations on extrusion of natural fiber and polymer matrices and the extrusion parameters involved. Extrusion compounding addresses composite molding problems such as non-homogeneous mixture and separation of fiber from polymer during rotational molding, which consequently affects engineering properties.

- **Extruders**

  The main function of an extruder is to develop sufficient pressure in the material to force the material through the die. The pressure necessary for this depends on the geometry of the die, the flow properties of the material and the flow rate. Basically, an extruder is a machine capable of developing pressure. In other words, an extruder is a pump. Extruders are used not only in extrusion operations; most molding operations also use an extruder, injection molding and blow molding, for example.

![Diagram](image)

Fig. 1.25 The extrusion compounding process for the manufacture of short fiber Reinforced thermoplastic injection moulding granules.
In the industry, there are three main extruder types: the screw extruder, which is the most common, the ram extruder, and the drum or disk extruder, which is the least common. In a screw extruder, a screw rotates in a cylinder; the rotation of the screw creates a pumping action. A screw extruder can have one screw or more.

An extruder with one screw is called a single screw extruder; it is the most common machine in the plastics processing industry. An extruder with more than one screw is called a multi-screw extruder, the most common of which is the twin-screw extruder (which has two screws). There are several types of twin-screw extruders. In most twin-screw extruders, the screws are located side by side. If both screws rotate in the same direction, the extruder is called a co-rotating twin-screw extruder. If the screws rotate in opposite directions, it is called a counter-rotating twin-screw extruder. Twin-screw extruders can run at high or low speed, depending on the application. High-speed extruders run at approximately 200-500 rpm or higher; they are primarily used in compounding. Low speed extruders run at approximately 10-40 rpm and are used mostly in profile extrusion applications. Most twin-screw extruders for profile extrusion are counter-rotating extruders. This is because counter-rotating extruders tend to have better conveying characteristics than co-rotating extruders. Most twin-screw extruders have parallel screws, but some extruders have conical screws where the screws are not parallel. Another distinguishing feature of twin extruders is the extent that the screws intermesh. The screws can be fully intermeshing, partially intermeshing or non-intermeshing. Most twin-screw extruders are intermeshing. The advantage of non-intermeshing extruders is that they can have a very long length without problems with respect to metal-to-metal contact between the screws.

The length to diameter ratio (L/D) can be 100:1 or higher. The L/D of intermeshing twin-screw extruders is generally limited to values less than 50:1. A disadvantage of current non-intermeshing twin screws is that they have limited dispersive mixing capability. Mixing takes place both in the melting zone as well as in the melt-conveying zone of the extruder. The solid plastic typically moves in plug flow, which means that there is no relative motion between the solid plastic particles. As a result, there is little or no mixing in the solids
conveying zone. This means that complete mixing does not start until all the plastic has melted. [1,2]

Extrusion is one of the most effective methods of compounding natural fibers and thermoplastic polymers. A thermoplastic polymer (which is usually obtained in pellet or powder form) and short reinforcing fibers are combined and drawn into a heated extrusion barrel by means of a single screw or two co-rotating screws, depending on the type of extruder. The polymer is melted and mixed with the fibers to form a composite melt, which is then drawn forward through the extruder barrel and further mixed and compressed to improve the melt homogeneity. The extruder melt then exits the barrel through a shaped die, which determines the shape of the extruded composite. Extrusion of short fiber reinforced thermoplastic composites using a twin-screw extruder is often carried out prior to injection moulding because of the excellent fiber distribution that can be achieved within the polymer matrix. The extruded composite can then be chopped into pellets that can easily be injection moulded into more complex shapes.

To produce composites with optimum mechanical properties and fiber distribution, it is necessary to optimise the extruder processing variables, such as barrel length, temperature profile, screw configuration and screw speed. Incorrect extruder set-up can result in poor dispersion and wetting of the fibers with the polymer matrix, as well as severe fiber damage and length reductions.

Most fiber damage is caused by inter-fiber friction, friction between fibers and polymer, and friction between fibers and the extruder. One method of minimizing fiber breakage is to feed the polymer into the main in-feed port and to feed the fibers into a second port further down the barrel, as can be seen in Figure. This enables the polymer to melt before coming into contact with the fibers, thus reducing the shear forces acting on the fibers. A second method of preserving the fiber integrity during compounding is to keep the compounding distance as short as possible, and also to minimize the number of kneading elements on the extruder screws.

Another variable that can affect the composite strength is processing temperature. If the temperature is too low, the polymer matrix will be too viscous to flow around the fibers, resulting in poor fiber wetting and hence a weaker composite. If the temperature is too high,
degradation of the fibers and polymer will occur, also resulting in composite strength reductions. Unlike melt mixing, extrusion is a continuous process that can accommodate high feed rates and allows the fast and efficient processing of materials. A shaped die can also be used to create a finished product with a desired profile.

Screw speed must be maintained at a high rate in order to minimize residence time and maximize throughput. However, when a product is heat sensitive, extruder screw speed is limited by the maximum shear rate that the product can experience without degradation. Another reason for limiting screw speed is to avoid air entrapment and to prevent excessive melt temperatures. If the polymer is extruded at rates that are too high, air entrapment can occur, resulting in tiny bubbles in the extrudate.

- **Extrusion Equipment**

  Figure 1.26 shows a basic extruder machine. Plastic pellets or beads (also referred to as resin) are fed from the hopper along a feed screw through a barrel chamber. As the resin travels along the barrel, it is subject to friction, compression, and heated zones. The result is that the resin melts and further travel at the exit end of the screw serves to mix the melt homogeneously. The melt enters a chamber designed to ensure an evenly distributed flow to the die. In many machines, a melt pump is used to prevent any pressure surges. Also, breaker plates serve to prevent any solid particles or foreign objects from passing through the die.

  The die is a precisely machined part with a patterned opening such that the extruded plastic takes that die pattern for its cross sectional area. With products such as extruded sheet, there are adjustments to the die to allow for a variety of sheet thickness with one die. Shapes are varied, and typically are holes for filament, annular rings for pipe and tube, or geometric patterned shapes for items such as vinyl siding and window frame stock. All die surfaces must be free from defects otherwise unwanted patterns will appear on the extruded product.

  Product from the die solidifies quickly. Depending on the end product, this may be achieved by immersion in cooling water, cooling, or contact with chill rolls. As mentioned above, overheating the melt is to be avoided at all costs, or the product will not form properly on solidification. Once solid, the product material can be wound, spun, or cut in defined lengths depending upon its intended end-use.
The major components in an extruder are briefly discussed here.

- Feed screw

As the only moving part in many extruders, feed-screws must do the job of moving the resins through the barrel chamber in a steady and predictable manner. As a result, and the feed-screw is critical to the design.

Figure 1.27 shows examples of feed screws. There are at least three defined sections in a basic feed screw, and if specifically engineered to accomplish a definite purpose, they can have additional sections.

![Fig. 1.26 Extrusion machine](image)

![Fig. 1.27 Feed Screws](image)
The feed zone takes resin from the hopper and conveys it along. During the journey, resin pellets encounter friction from feed screw surfaces, barrel surfaces, and each other. This mechanical friction is about 85% of the required heat, so it is critical that the drive equipment to turn the screw have the HP capabilities to overcome friction and turn the feed screw at a steady and controlled rate. Some extruders can continue to plasticate materials long after their external heat sources are shut down. The compression zone is next. Here, the channel depth between screw flights diminishes and the result is to pressurize the now melting resin. Friction, barrel heating, and compression in this stage should complete the melting process.

The metering zone has a constant channel depth and primarily exists to further mix molten resin. The end result is a smooth consistent melt with uniform temperature. In some processes, a de-gassing or devolatizing section is required. This is a shorter zone that immediately follows the compression zone. Channel depth is suddenly increased, and the resulting pressure drop causes a release of any gas, which can be vented or drawn off via vacuum pump. The remaining melt is re-compressed and metered.

Mechanical screw design also requires the selection of high-grade materials and precision machining. The screw must fit tightly in the barrel to prevent excessive back-flow or drag flow of resin due to excessive gaps between the screw flights and the barrel surface. It must not be so tight that it contacts the barrel surface itself, causing grooves and other damaging effects.

- **Barrel Chamber**

This thick-walled steel chamber that is expected to withstand high pressures (~ 20,000 psi/137Mpa), is precisely machined for a tight fit with the feed screw, and has a hardened steel alloy on its inside wall to prevent wear and corrosion. Some barrels will also have a grooved feed zone to increase the frictional forces on the resin.

The barrel also is heated to facilitate melting of the resin. Although the major contributor to melting is friction, the heat as conducted through the barrel can serve as a "fine adjust" or vernier in temperature control and energy input. Electrical resistance heating is a common method employed. Advantages are that several temperature zones can be set up with multiple elements, and temperature profiles can be created as material requirements vary.
When thermal needs are not so complex, steam heating via a jacketed barrel chamber. A jacketed chamber uses cooling water to prevent overheating of the melt in the vicinity of the die as well.

- **Dies**

The opening that allows plasticated material to form particular shapes is also a highly engineered part. Dies are designed to compensate for effects of shrinkage when a melt re-solidifies, two dimensioned size adjustments, and varying rates of solidification. Dies must be free from defects and scratches; otherwise the melt could show the defect's pattern.

The flow of melt to the die typically follows a tapered path, with the die having a thickness associated with it. This results in the melt undergoing a pressure drop as it exits the die, and this prevents unwanted build-up at irregular places along the die, which would spoil the product. Dies can take on a variety of shapes and have adjustable openings. In the case of filament extrusion and others, multiple duplicate die patterns to extrude many strands in parallel can be found on a single die.

- **Injection Moulding**

Injection moulding is one of the most widely used processes for manufacturing moulded parts from thermoplastic and reinforced thermoplastic materials. It is one of the few manufacturing processes capable of producing net shape composite parts in high volumes and at high production rates. Short fiber reinforced composites can be processed into complex shaped components using standard thermoplastic injection moulding equipment.

Composite materials for use in injection moulding applications must be capable of fluid-like flow during processing, and thus usually consist of short fibers with a relatively low fiber fraction (typically <50wt% or 30vol%). The composite fiber content needs to be carefully considered, as low fiber content can result insufficient reinforcement, and high fiber content can lead to poor moulding and reduced mechanical properties of the composite.
Fig. 1.28 Basic operations of the injection moulding cycle: (a) start up; (b) screw back 1; (c) injection; (d) hold-on; (e) screw back 2; (f) cooling and ejection.

The injection moulder performs the function of melting the pre-formed (usually by extrusion) composite pellets in a heated barrel, delivering a homogeneous melt to the machine nozzle, and injecting the melt into a closed mould. The mould unit, which comprises of a fixed section and a movable section, encloses the shaped cavity into which the composite is injected and cooled, and is thus responsible for determining the final shape of the moulded part (Figure 1.28).

The injection moulding process does not induce the same level of mechanical friction on the composite melt as do other fabrication processes such as extrusion and melt mixing, and it has been found that injection moulding does not lead to significant reinforcing fiber damage.

- **The Injection Moulding Cycle**

The modern day process has developed and matured significantly to the level where fully automated, closed loop, microprocessor controlled machines are the 'norm', although in principle injection moulding is still a relatively simple process. Thermoplastic injection moulding requires the transfer of the polymeric material in powder or granule form from a
feed hopper to a heated barrel. In the barrel, the thermoplastic is melted and then injected into a mould with some form of plunger arrangement. The mould is clamped shut under pressure within a platen arrangement and is held at a temperature well below the thermoplastic melt point. The molten thermoplastic solidifies quickly within the mould, allowing ejection of the component after a pre-determined period of cooling time. The basic injection moulding process steps with a reciprocating screw machine are as follows.

- **Mould Close and Clamping**

  The mould is closed within the platen arrangement and clamped using necessary force to hold the mould shut during the plastic injection cycle, thus preventing plastic leakage over the face of the mould. Present day moulding machines range from around 15 to 4,000 metric tonnes available clamping force (150 to 4000 KN).

  Many systems are available for opening/closing and clamping of mould tools, although usually they are of two general types. Direct Hydraulic Lock is a system where the moving machine platen is driven by a hydraulic piston arrangement, which also generates the required force to keep the mould shut during the injection operation. Alternatively, smaller auxiliary pistons may be used to carry out the main movement of the platen and a mechanical blocking arrangement is used to transfer locking pressure from a pressure intensifier at the rear of the machine, which moves only by a few millimeters, through to the platen and tool.

  The second type of general clamping arrangement is referred to as the Toggle Lock. In this case a mechanical toggle device, which is connected to the rear of the moving platen, is actuated by a relatively small hydraulic cylinder; this provides platen movement and also clamping force when the toggle joint is finally locked over rather like a knuckle arrangement.

- **Injection**

  At this stage in the machine cycle the helical form injection screw (Figure 1.29) is in a 'screwed back' position with a charge of molten thermoplastic material in front of the screw tip roughly equivalent to or slightly larger than that amount of molten material required to fill the mould cavity. Injection moulding screws are generally designed with length to diameter ratios in the region of 15:1 to 20:1, and compression ratios from rear to front of around 2:1 to 4:1 in order to allow for the gradual densification of the thermoplastic material as it melts. A check
valve is fitted to the front of the screw such as to let material pass through in front of the screw tip on metering (material dosing), but not allow material to flow back over the screw flights on injection. The screw is contained within a barrel, which has a hardened abrasion resistant inner surface.

![Fig. 1.29: Reciprocating screw injection moulding unit](image)

Normally, ceramic resistance heaters are fitted around the barrel wall, these are used to primarily heat the thermoplastic material in the barrel to the required processing temperature and make up for heat loss through the barrel wall, and due to the fact that, during processing most of the heat required for processing is generated through shear imparted by the screw. Thermocouple pockets are machined deep into the barrel wall so as to provide a reasonable indication of melt temperature. Heat input can therefore be closed loop controlled with a Proportional Integral and Derivative (PID) system. The screw (non-rotating) is driven forward under hydraulic pressure to discharge the thermoplastic material out of the injection barrel through the injection nozzle, which forms an interface between barrel and mould, and into the moulding tool itself.

- **Holding Pressure and Cooling**

  The screw is held in the forward position for a set period of time, usually with a molten 'cushion' of thermoplastic material in front of the screw tip such that a 'holding' pressure may be maintained on the solidifying material within the mould, thus allowing compensating material to enter the mould as the moulded part solidifies and shrinks. Holding pressure may be initiated by one of three methods: by a set time in seconds from the start of the injection fill...
phase; by the position of the screw in millimeters from the end of injection stroke; or by the rise in hydraulic pressure as measured by a pressure transducer in the mould itself or in the injection hydraulic system.

As the material solidifies to a point where hold pressure no longer has an effect on the mould packing, the hold pressure may be decayed to zero, this will help minimise residual stresses in the resultant moulding. Once the hold pressure phase has been terminated the mould must be held shut for a set period of cooling time. This time allows the heat in the moulding to dissipate into the mould tool such that the moulding temperature falls to a level where the moulding can be ejected from the mould without excessive distortion or shrinkage. This usually requires the moulding to fall to a temperature below the rubbery transition temperature of the thermoplastic or Tg (glass transition temperature). Depending on the type of plastic this can be within a few degrees or over a temperature range. Mould temperature control is incorporated into the tool usually via channels for pressurized water flow. The mould may be connected to a cooling unit or water heater depending on the material being processed, type of component and production rate required.

- **Material Dosing or Metering**

  During the cooling phase, the barrel is recharged with material for the next moulding cycle. The injection screw rotates and, due to its helical nature, material in granule or powder form is drawn into the rear end of the barrel from a hopper feed. The throat connecting the hopper to the injection barrel is usually water cooled to prevent early melting and subsequent material bridging giving a disruption of feed. The screw rotation speed is usually set in rpm, which is measured using a proximity switch at the rear of the screw. Screw rotation may be set as one constant speed throughout metering or as several speed stages.

  The material is gradually transferred forward over the screw flights and progressively melted such that when it arrives in front of the screw tip it should be fully molten and homogenized. The molten material transferred in front of the tip progressively pushes the screw back until the required shot size is reached. Increased shear is imparted to the material by restricting the backward movement of the screw; this is done by restricting the flow of hydraulic fluid leaving the injection cylinder. This is referred to as 'back pressure' and it helps
to homogenize the material and reduce the possibility of un-melted material transferring to the front of the screw.

- **Mould Open and Part Ejection**

  When the cooling phase is complete the mould is opened and the moulding is ejected. This is usually carried out with ejector pins in the tool, which are coupled via an ejector plate to a hydraulic actuator, or by an air operated ejector valve on the face of the mould tool. The moulding may free fall into a collection box or onto a transfer conveyer, or may be removed by an automatic robot. In this latter case the moulding cycle is fully automatic. In semi-automatic mode, the operator may intervene at this point in the cycle to remove the moulding manually. Once the moulding is clear from the mould tool, the complete moulding cycle can be repeated.

- **Compression Moulding**

  Compression moulding (hot pressing) is a commonly used processing technique for producing large, relatively simple composite parts with good mechanical properties. The compression moulding of glass mat reinforced thermoplastics is widely used in the production of complex semi-structural components, notably for the automotive industry. Compression moulding basically involves the hot pressing of randomly orientated or aligned fiber mats, either chopped or in continuous form, with a thermoplastic material. The compression moulding operation begins with the placement of a stack of alternating fiber-mat and thermoplastic sheets onto the bottom half of a preheated mould cavity. The top half of the mould is lowered at a constant rate until the desired processing pressure is reached, thus causing melting of the polymeric matrix and consolidation of the composite. Once the composite has been pressed, it is cooled and removed from the mould.

1.21 **Challenges in Natural Fibre Composites**

  From the foregoing, it becomes evident that newer composites using abundantly available natural fibres are on the horizon, thus bringing new trends in composite materials. But to make this a reality, the following conditions may have to be met:
(i) Since natural fibres are not available in the required length and form (filaments, mats, ribbons, fabrics, non-wovens, rovings, etc.), first attempts should be made to develop processes to obtain the natural fibres in the required form.

(ii) Attempts should be made to minimize the resin consumption and moisture absorption by the natural fibres through simple and economic processes, keeping in mind the establishment of this fibre industry in rural and semi-urban areas. Suitable inexpensive resins (from lignocellulosic materials) should be developed for better performance and better compatibility with natural fibres. Some attempts in this direction are being made.

(iii) Since natural fibres are organic in nature and absorb moisture, degradation of composite materials based on them will be one of the major limitations for durability. Similarly, fire hazard is another problem. Processes should be developed to minimize these limitations. Suitable fabrication techniques for manufacture should be developed keeping in view that this is a low-technology area and hence must be cost-effective.

(iv) Physical, mechanical, thermal, electrical, optical, tribological and environmental properties of these natural fibre-polymer composites with and without hybridization should be evaluated completely so as to arrive at a series of composites which may find uses in several areas such as the marine, structural, consumer-articles, and electrical industries. This implies that suitable design data should be developed so as to popularize use of these new materials. Further evaluation of ageing effects of natural fibres when hybridization is attempted is to be made.

(v) Since natural fibre-polymer composites do not give the expected strength values derived from the rule of mixtures, detailed basic studies on factors related to strength, such as interface bonding and fracture mechanisms, are to be carried out to facilitate future development of these composites for suitable applications.