STUDIES ON THE PROPERTIES OF WOVEN NATURAL FIBERS REINFORCED UNSATURATED POLYESTER COMPOSITES

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2008

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WOVEN NATURAL FIBERS REINFORCED
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by

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Thesis submitted in fulfillment of the requirements for the degree of

Master of Science

September 2008

Declaration

I declare that this thesis is the result of my own research, that it does not incorporate without acknowledgement any material submitted for the degree or diploma in any university and does not contain any materials previously published, written or produced by another person except where due references are made in the text.

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ACKNOWLEDGEMENT

Bismillahirrahmanirrahim...

Alhamdulillah, thanks to Allah for giving me the opportunity to finish my research study successfully.

First of all, I would like to express my gratitude to my main supervisor, Dr. Mariatti Jaafar, who had supportively guiding and helping me in so many things throughout the research project. Thanks for the good advices and encouragements. I am also grateful to my co-supervisor, Dr. Azhar Abu Bakar for giving some advices in improving my work.

Special thanks to all the administrative staffs and academic staffs which is lead by the Dean of School of Materials and Mineral Resources Engineering, Prof. Khairun Azizi Mohd Azizli for their help and support in this research project. Guidance from Associate Prof. Dr. Azizan Aziz, Deputy Dean (postgraduate and research) and Associate Prof. Dr. Abdul Khalil Shawkataly (School of Industrial Technology, USM Penang), are much appreciated. For the technical staff of the school especially Mr. Khairul Nasrin, Mr. Sayuti, Mr. Sharul Ami, Mrs. Fong, Mr. Abdul Razak, Mr. Gnanasegaram, Mr. Rashid, Mr. Shahid, Mr. Mohammad, Mrs. Hasnah, Mr. Kemuridan, Mr. Mokhtar, Miss Mahani, Mr. Hasnor, Mr. Helmi, Mr. Sa'arani, Mr. Halim, Mr. Faizal, Mr. Rokman, Mr. Suhaimi, Mr. Azam, Mrs. Haslina, Mr. Zaini, Mr. Farid, Mr. Fitri, Mr. Azrul, Mr. Shahril and Mr. Zulkurnain who had assisted and guided me during my research study. Thanks a lot.

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LIST OF ABREVIATIONS

ASTM   American Standard for Testing and Materials

AA   Acrylic Acid

DP   Degree of polymerization

FESEM   Field-Emission Scanning Electron Microscopy

FRIM   Forest Research Institute of Malaysia

Fig.   Figure

FTIR   Fourier-Transform Infrared Spectroscopy

H_2O Water

MEKP   Methyl ethyl ketone peroxide

MW   Molecular Weight

Na^+ Natrium

NaOH   Sodium Hydroxide

O^- Oxygen

OH   Hydroxide

S_2 Sulphur molecule

Sdn. Bhd.   Sendirian Berhad

SEM   Scanning Electron Microscopy

TAPPI   Technical Association of the Pulp and Paper Industry

T_g Glass transition temperature

USP   Unsaturated Polyester

LIST OF SYMBOLS

cm	Centimeter
cm^2	Centimeter square
cm^3	Centimeter cube
cm^{-1}	Per centimeter
D	Diameter
g	Gram
g/cm^3	Gram per centimeter cube
$g.mol^{-1}$	gram per mole
GPa	Giga Pascal
hrs.	Hours
J	Joule
kg	Kilogram
kJ/m^2	Kilo Joule per meter square
L	Length
m	Meter
ml	Milliliter
min.	Minute
mm	Millimeter
MPa	Mega Pascal
m^2s^{-1}	Meter square per second
Pa	Pascal
V	Volume
vol. %	Volume percentage
W	Weight

α	Alpha
β	Beta
$^{\circ}$	Degree
$^{\circ}$C	Degree Celcius
%	Percentage
<	Less than
μm	Micrometer
ρ	Density
±	Plus minus

KAJIAN SIFAT-SIFAT KOMPOSIT POLIESTER TAK TEPU
DIPERKUAT ANYAMAN GENTIAN-GENTIAN SEMULAJADI

ABSTRAK

Komposit poliester tak tepu (USP) diperkuat anyaman gentian pisang dan mengkuang telah dihasilkan melalui teknik beg vakum. Sifat-sifat pelenturan, hentaman dan penyerapan air telah dikaji berdasarkan pecahan isipadu gentian. Sifat-sifat mekanikal kedua-dua komposit gentian semulajadi didapati lebih tinggi daripada resin USP. Bagaimanapun, sifat-sifat pelenturan dan hentaman kedua-dua sistem komposit anyaman masing-masing menurun bagi pecahan isipadu melebihi 10 dan 15 peratus disebabkan pembasahan tak sempurna. Komposit anyaman pisang menunjukkan sifat mekanikal yang tinggi disebabkan oleh dinding sel yang tebal dan kandungan selulosa yang tinggi iaitu sebanyak 67.3 % berat berbanding 44.4 % berat bagi komposit anyaman mengkuang. Ujian penyerapan air menunjukkan komposit anyaman mengkuang meningkatkan keseluruhan penyerapan air berbanding komposit anyaman pisang disebabkan oleh kandungan hemiselulosa dan lignin yang tinggi dan wujud kecacatan dalam sistem komposit. Untuk komposit gentian pisang terawat, rawatan asid akrilik (AA) menunjukkan peningkatan sifat mekanikal dan penyerapan air berbanding komposit gentian terawat sodium hidroksida (NaOH) dan gentian tanpa rawatan. Dalam kajian komposit hibrid, laminat pisang-kaca-pisang (BGB) dan kaca-pisang-kaca (GBG) menunjukkan sifat mekanikal yang tinggi berbanding komposit laminat gentian pisang (BBB). Komposit laminat gentian kaca (GGG) menunjukkan sifat mekanikal tertinggi disebabkan oleh sifat mekanikal gentian kaca (G) yang begitu tinggi. Melalui hibriditasi gentian kaca, peratusan kandungan kelembapan komposit gentian pisang menurun disebabkan oleh penyerapan air yang rendah yang telah ditunjukkan oleh gentian kaca.

STUDIES ON THE PROPERTIES OF WOVEN NATURAL FIBERS REINFORCED UNSATURATED POLYESTER COMPOSITES

ABSTRACT

Woven banana fiber and pandanus fiber reinforced unsaturated polyester (USP) composites were fabricated by vacuum bagging technique. Flexural, impact and water absorption properties were investigated as a function of fiber volume fraction. It is found that the mechanical properties of both natural fiber reinforced USP composites are higher than USP resin. However above 10 and 15 vol. fraction of fibers, the flexural and impact properties of these two woven composite systems decreased due to poor wetting, respectively. Banana woven composites exhibit higher mechanical properties due to the thicker cell wall in fiber structure and higher fiber cellulose content which is 67.3 wt. % compared to that of 44.4 wt. % for pandanus woven composites. Water absorption test showed that woven pandanus fabric composites increased the overall water uptake than woven banana fabric composites due to higher hemicellulose and lignin content and the defects existed in the composite system. For treated banana fiber composites, the acrylic acid (AA) treatment results in improved mechanical and water absorption properties compared to the composites with sodium hydroxide (NaOH) treated fiber and untreated fibers. In the study of hybrid composites, laminates of banana-glass-banana (BGB) and glass-banana-glass (GBG) exhibit higher mechanical properties compared to banana fiber laminates composite (BBB). As expected, glass fabric laminate composite (GGG) shows the highest mechanical properties due to the superior mechanical properties of glass fiber (G). By hybridization with glass fiber, the percentage of moisture content of banana fiber composites decreased due to low water absorption shown by glass fibers.

CHAPTER 1

INTRODUCTION

1.1. Background

Fiber reinforced composite materials are an important class of engineering materials. They offer outstanding mechanical properties, unique flexibility in design capabilities and ease of fabrication (Agarwal and Broutman, 1990). Composites using high strength fibers such as graphite, aramid and glass are commonly used in broad range of applications from aerospace structure to automotive parts and from building materials to sporting goods (Arib et al., 2006). However, the development of natural fiber reinforced composites become an attractive research lines due to the non-recyclability, high density and health hazards of composites reinforced with synthetic fibers such as glass, carbon and aramid fibers (Corrales et al., 2007; Herrera and Valadez, 2005). Besides, the greatest problem of using such materials is how to conveniently dispose of them once they have come to the end of their useful life span (Bodros et al., 2007). Therefore, there has been growing interest in the use of natural cellulosic fibers as the reinforcement for polymeric matrix. Several natural fibers such as sisal (Chow et al., 2007), jute (Ahmed et al., 2007), flax (Baley et al., 2006), pineapple (Tran, 2006), bamboo (Shih, 2007), kenaf (Shibata et al., 2006), bagasse (Cao et al., 2006; Vilay et al., 2008) fibers and so on have been studied as a reinforcement and filler in polymer composites.

The utilization of natural fiber has gained attentions due to the reduction of waste disposal problems especially in agricultural fields, environmental pollution (Nishino, 2004) and can find various applications in engineering, electronic and automotive fields (Goda et al., 2006). Green, environmentally friendly, sustainable, renewable, biodegradable, composites from natural fibers are among the most keenly required materials nowadays (Bledzki and Gassan, 1999; Mohanty et al., 2000). Most cellulosic fibers are harvested yearly and the supply should be inexhaustible compared to the limited supply of oil reserve from which many synthetic fibers are derived (Arib et al., 2006). Natural fibers reinforced polymers also have exhibited numerous advantages such as high mechanical properties, low weight, low cost, low density, high specific properties (Manfredi et al., 2006), posses better electrical resistance, good thermal and acoustic insulating properties and higher resistance to fracture (Gowda et al., 1999). Additionally, the natural fibers reinforced composites can decrease wearing of machines due to its low abrasiveness and absence of health hazardness during processing, application and upon disposal (Goda et al., 2006).

1.2 Problem statement

Natural fibers can be produced in many types of reinforcement composites, such as continuous and discontinuous unidirectional fibers, random orientation of fibers, etc. By taking the advantages from those types of reinforced composites such as produced good properties and reduced the fabrication cost, they had been used in the development of automotive, packaging and building materials. A growing interest in woven composites has been observed in recent years. A woven fabric contains fibers oriented on at least two axes, in order to provide great strength and stiffness. Woven composites are known to be complex systems, which have additional features such as, interlace

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spacing or gap, interlace point and unit cell (Mariatti et al., 2000). There are very few reports on woven fabric composites reported so far. The popularity of woven composites is increasing due to simple processing and acceptable mechanical properties (Jekabsons and Bystrom, 2002). Woven fabric composites provide more balanced properties in the fabric plane than unidirectional laminas (Jang, 1994). According to Khashabaa and Seif (2006), the usage of woven composites has increased over the recent years due to their lower production costs, light weight, higher fracture toughness and better control over the thermo-mechanical properties. The weaving of the fiber provides an interlocking that increases strength better than can be achieved by fiber matrix adhesion. Failure of the composite will require fiber breakage, since fiber pullout is not possible with tightly woven fibers (Shanks, 2004). Based on our knowledge, there are less works having been done on the woven natural fiber composites.

Realizing the advantageous of natural fibers and woven pattern, these two factors have been considered in the present work. In this research project, two types of natural fibers; banana and pandanus were utilized as reinforcement. These two types of natural fibers were used because of their ability to be produced in a continuous form, and hence able to be produced into a woven mat form.

1.3 Research objectives

The objectives of the study are:

1. To characterize the properties of banana and pandanus fibers.

2. To characterize, compare and optimize the properties of banana and pandanus fibers for use as reinforcement in unsaturated polyester resin.

3. To evaluate the effect of fiber treatments using sodium hydroxide (NaOH) and acrylic acid (AA) on the properties of woven banana reinforced unsaturated polyester composites.

4. To study the effect of different laminate configuration (3-ply laminated composites) on the properties of hybrid woven banana fiber and woven glass fiber reinforced unsaturated polyester composites.

1.4 Organization of thesis

In this thesis, the background theory and the relevant literature survey are presented in the first chapter and second chapter, respectively. This is followed by chapter three, where descriptions of all the materials and methods used in experiments characterization and test procedures are explained. Chapter four contains the details of the results and discussion. Last but not least, chapter five presents the conclusions of this thesis and some suggestions for future works.

CHAPTER 2

LITERATURE REVIEW

2.1 Types of fibers

Fibers are class of hair-like materials that are in discrete elongated pieces, similar to pieces of thread (Natural, 2007). 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 (Cooke, 1989). 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 2.1.
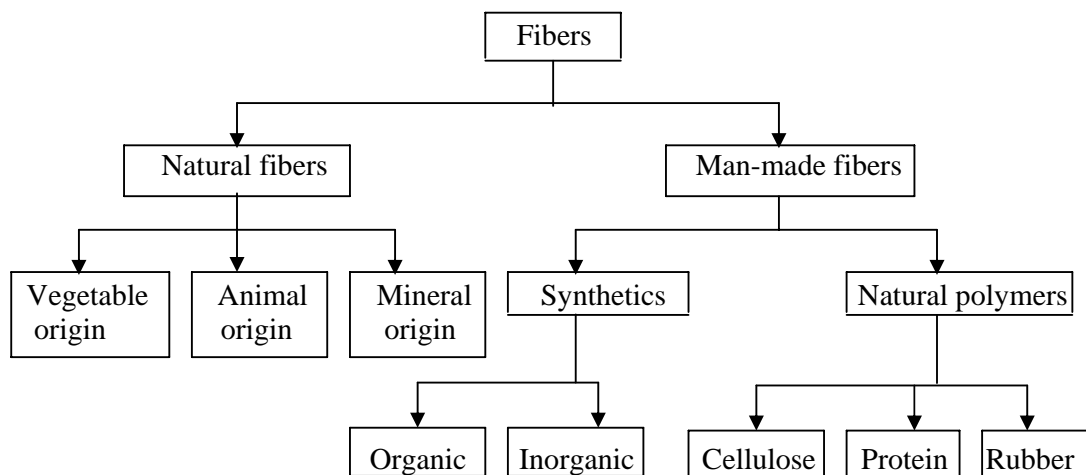
Figure 2.1: Classification of fibers (Cooke, 1989).

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 (Agarwal and Broutman, 1990). 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 (Agarwal and Broutman, 1990). 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. Figure 2.2 represents an accepted classification of single-layer alignments.
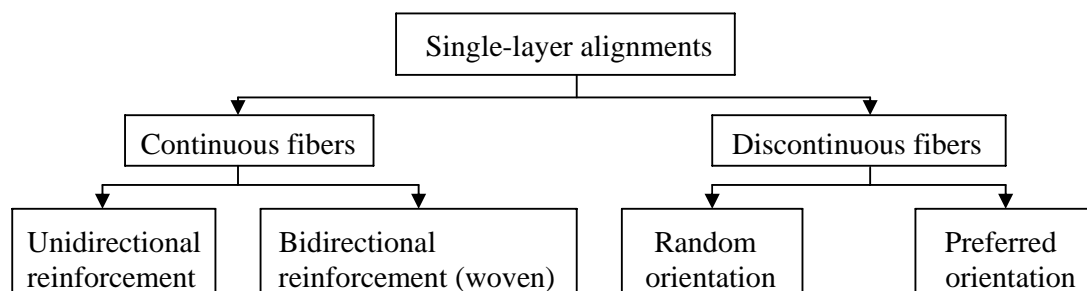
Figure 2.2: Single-layer alignments (Agarwal and Broutman, 1990).

2.1.1 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 (Synthetic, 2007). 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 (Cooke, 1989).

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 (Hannant, 1989). 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 (Cooke, 1989).

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 (Agarwal and Broutman, 1990). Glass fiber is the dominant fiber and is used in 95 % of cases to reinforce thermoplastic and thermoset composites (Mohanty et al.,

2005). The principal advantages of glass fibers are low cost and high strength 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 2.3.

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                              ┌─────────────┐
                              │  Synthetics │
                              └─────────────┘
                    ┌──────────────────┴──────────────────┐
              ┌──────────┐                          ┌───────────┐
              │ Organic  │                          │ Inorganic │
              └──────────┘                          └───────────┘
  ┌──────────┬──────────┬──────────┬──────────┬──────────┬──────────┐
┌──────────┐┌──────────┐┌──────────┐┌──────────┐┌──────────┐┌──────────────┐
│Polyamides││Polyesters││Polyacrylics││Polyolefin││Elastomers││Miscellaneous │
└──────────┘└──────────┘└──────────┘└──────────┘└──────────┘└──────────────┘
```

| Polyamides | Polyesters | Polyacrylics | Polyolefin | Elastomers | Miscellaneous |

Aramid
Nylon 6
Nylon 66

Polyacrylonitrile
Modacrylic

Spandex

Polyethylene terephthalate

Polyethylene
Polypropylene

Polyimide
Polybenzimidazole
Others

| Silicon | Carbon graphite | Aluminum | Boron | Miscellaneous |

Glass
Silica
Silicon carbide

Aliminosilicate
Alumina

Boron carbide
Boron nitride

Zirconia
Titania
Others

Figure 2.3: Classification of synthetic fibers (Cooke, 1989).

2.1.2 Natural fibers

Natural fibers are subdivided based on their origins, for example vegetable/plants, animals, or minerals. Figure 2.4 shows the classification of natural fibers. Vegetable or plant fibers include bast or stem fibers, leaf or hard fibers, seed, fruit, wood, cereal straw and other grass fibers (Alexander et al., 2005). According to Jeronimidis (1989), plants can stand up because of cellulose and lignin. Structural materials in animals are mainly made of proteins such as collagen, elastin and keratin in combination with various polysaccharides, calcium minerals (in bone and teeth) or complex phenolic compounds (in hard insect cuticles). Mineral fibers are naturally occurring fiber or slightly modified fiber procured from minerals. Mineral fibers such as asbestos fibers had been used historically for insulating houses. However, since January 1997, to provide protection of workers and consumers, the manufacture and transformation of asbestos fibers became forbidden (Bilba et al., 2007).
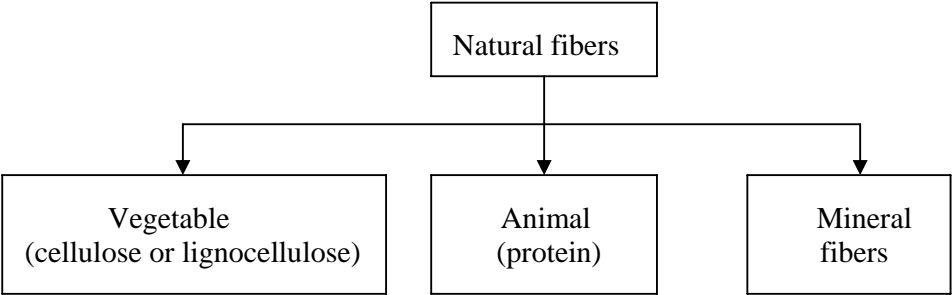
Figure 2.4: Classification of natural fibers (Alexander et al., 2005).

Natural fibers are now emerging as viable alternatives to glass fibers either alone or combined in composite materials for various applications. The advantages of natural fibers over synthetic or man-made fibers such as glass are their relatively high stiffness, a desirable property in composites, low density, recyclable, biodegradable, renewable

raw materials, and their relatively low cost (Mohanty et al., 2005; Frederick and Norman, 2004; Joseph et al., 2002). Besides, natural fibers are expected to give less health problems for the people producing the composites. Natural fibers do not cause skin irritations and they are not suspected of causing lung cancer (Bos, 2004). The disadvantages are their relatively high moisture sensitivity and their relatively high variability of diameter and length. The abundance of natural fibers combined with the ease of their processability is an attractive feature, which makes it a covetable substitute for synthetic fibers that are potentially toxic (Pothan et al., 2006).

2.2 Natural fiber definition

"Natural" fibers in the strict meaning of the word are produced through agriculture (Schuster et al., 2004). Natural fibers are a composite material designed by nature. The fibers are basically a rigid, crystalline cellulose microfibril-reinforced amorphous lignin and hemicelluloses matrix. Most plant fibers, except for cotton, are composed of cellulose, hemicelluloses, lignin, waxes and some water-soluble compounds, where cellulose, hemicelluloses and lignin are the major constituents.

From a structural point of view, natural fibers are multicellular in nature, consisting of a number of continuous, mostly cylindrical honeycomb cells which have different sizes, shapes and arrangements for different types of fibers (Dipa and Jogeswari, 2005). These cells are cemented together by an intercellular substance which is isotropic, noncellulosic and ligneous in nature, with a cavity termed the lacuna, whose position and dimensions differ in composition and orientation of cellulosic microfibrils. There is a central cavity in each cell called the lumen (Dipa and Jogeswari, 2005). The microfibrils in the central walls form a constant angle (microfibrillar or helical angle)

for each type of fiber with the fiber axis, so that the crystallites are arranged in a spiral form, the pitch of which varies from one fiber to another. Thus, each fiber is a 'natural composite' by itself, wherein crystallites (mostly cellulosic) remain rooted in a matrix in a given orientation. Hence the properties of the single fibers depend on the crystallite content, their sizes, shape, orientation, length/diameter (L/D) ratio of cells, thickness of cell walls, and finally, their defects such as lumen and lacuna (Dipa and Jogeswari, 2005).

Dipa and Jogeswari (2005) summarized that the most important factor controlling the different types of natural fibers is their species because the properties of fibers are different between different species. In addition, the properties of fibers within a species vary depending on area of growth, climate and age of the plant. Lastly, the properties of natural fibers vary greatly depending on their processing method used to break down to the fiber level.

2.3 Classification of vegetable or plant fibers

Vegetable or plant-based natural fibers are lignocellusic, consisting of cellulose microfibrils in an amorphous matrix of lignin and hemicellulose. They consist of several hollow fibrils which run all along their length (Prasad, 1989). Each fibril exhibits a complex layered structure, with a thin primary wall encircling a thicker secondary layer, and is similar to the structure of a single wood-pulp fiber. Nishino (2004) found that the primary (outer) cell wall was usually very thin (< 1 µm). The secondary layer is made up of the three distinct layers, the middle one (also known as S_2 layer) being by far the thickest and the most important in determining mechanical properties. Prasad (1989) point out that in this layer, parallel cellulose microfibrils are wound helically around the

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fibrils which the angle between the fiber axis and the microfibrils is termed the microfibril angle. Natural fibers are themselves cellulose-fiber-reinforced materials in which the microfibril angle and cellulose content determine the mechanical behavior of the fiber.

For fiber geometry, man-made fibers emerging from a spinneret are cylindrical, with approximately constant diameter and specific area. This is not the case for cellulosic fibers that present many defect caused by twisting in the stacking of the cellulosic chains (Herrera and Valades, 2005). These defects are apparent as 'knees' at the fiber surface and constitute points where the fiber may rupture more easily. In addition, an important parameter is the aspect ratio (length/diameter), which has an influence on the mechanical properties of the composite. This aspect ratio is highly modified by attrition during processing such as extrusion or injection.

According to Timothy and Michael (1997), vegetable fibers can be generally classified as bast, leaf, seed-hair, cereal straw or grass fibers, depending on their origin. Bos (2004) had illustrated the classification of vegetable fibers as shown in Fig. 2.5. In the plant, the bast and leaf fibers lend mechanical support to the plant's stem and leaf, respectively. Bast consists of a wood core surrounded by stem. Within the stem, there are a number of fiber bundles, each containing individual fiber cells or filaments. Bast fibers are usually grown in warm climates such as hemp, flax, jute, kenaf and ramie (Joseph et al., 2005). While for leaf fibers such as sisal, abaca, banana and henequen, they are coarser than bast fibers. In contrast, seed-hair fibers, such as cotton, coir and milkweed, are attached to the plant's seeds and aid in wind dispersal (Timothy and Michael, 1997). Joseph et al. (2005) reported that cotton is the most common seed fiber

and it is used for textile all over the world. Historically, humans have used all these natural fibers for textiles because of their wide availability, long fiber geometries, chemical stability, and favorable mechanical properties. The coarse texture and high mechanical properties of many bast and leaf fibers have made them common cordage fibers for rope, twine, and string (Timothy and Michael, 1997).

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                    ┌─────────────────────────┐
                    │   Vegetable / Plant     │
                    │ (Cellulose or lignocellulose) │
                    └─────────────────────────┘
     ┌──────────┬──────────┬──────────┬──────────┐
  ┌──────┐  ┌──────┐  ┌──────┐  ┌────────────┐  ┌──────┐
  │ Bast │  │ Leaf │  │ Seed │  │Cereal Straw│  │Grass │
  └──────┘  └──────┘  └──────┘  └────────────┘  └──────┘
  ┌──────┐  ┌────────────┐ ┌──────┐ ┌──────────┐ ┌────────────┐
  │ Flax │  │ Henequen   │ │Cotton│ │ Corn     │ │ Bamboo     │
  │ Jute │  │ Sisal      │ │ Coir │ │ Wheat    │ │ Switch grass│
  │ Hemp │  │ Pineapple leaf│       │ Rice straws│ │ Miscanthus │
  │ Kenaf│  └────────────┘ └──────┘ └──────────┘ └────────────┘
  └──────┘
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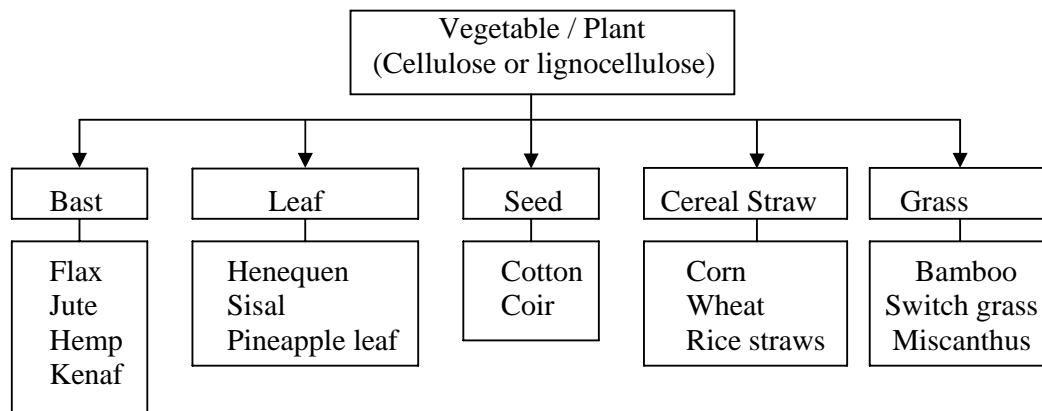
Figure 2.5: Classification of vegetable or plant fibers (Bos, 2004).

2.3.1 Bast and core fibers

Bast fibers exist in the inner bark or phloem of many dicotyledonous plants to provide structural rigidity to the stems. These fibers occur in bundles which run parallel to the stems between nodes. The fiber strands are composed of many smaller cells termed ultimate fibers. Just inside the phloem is a wood-like core material consisting of short and fine fibers (Timothy and Michael, 1997). According to Alexander et al. (2005), the shape and size of the stem of various bast fiber crops are different but they all contain varying amount of fiber cells in the phloem. Long individual fiber or long fibers bundles can be obtained from many bast fiber crops at relatively low cost.

However, bast fibers have a non-homogeneous cell structure than do the much shorter wood fibers which are uniform, readily available and inexpensive.

Bast fibers have been used for generations to produce textiles and are removed from the phloem by a controlled decay and separation process called retting. In general, the core material is unused after the outer bast fibers are removed (Timothy and Michael, 1997). Bast fiber crops have rigid herbaceous stalks containing nodes at regular intervals that are fluted or channeled. From the inside to outside the stalks have a hollow core, except at joints, followed by the pith and finally the protective layer epidermis (Alexander et al., 2005).

Characteristic geometries and dimensions for bast and core fibers are compiled in Table 2.1. In general, bast fibers strands are large with the average length of 25 to 120 cm and widths less than 1 mm. The ultimate fibers comprising these strands range in size (Timothy and Michael, 1997). For jute and kenaf, the ultimate fibers have a similar size to many coniferous wood species. However, for flax and hemp, they have extremely long ultimate fibers that are only minimally larger in diameter to wood. These fibers typically have aspect ratios (length/diameter) on the order of 1000.

Table 2.1: Dimensions of bast and core fibers (Timothy and Michael, 1997)

Type	Property	Flax	Hemp	Jute	Kenaf
Bast Strand.	Length (cm)	25-120	100-400	150-360	200-400
	Width (mm)	0.04-0.6	0.5-5	-	-
Bast Ultimate	Length (mm)	4-69	5-55	0.7-6	2-11
	Diameter (mm)	8-31	16	15-25	13-33
Core Ultimate.	Length (mm)	0.2	0.7	1.06	0.6
	Diameter (mm)	-	-	26	30

2.3.2 Leaf fibers

In many monocotyledons, long strand leaf fibers are embedded in parenchymatous tissue to provide mechanical support for the long and broad leaves. As in the bast, these composite fiber strands are composed of many smaller ultimate fibers (Timothy and Michael, 1997). In general, leaf fibers are more coarse than bast fibers and are commonly used as cordage, mats, rugs, and carpet backings rather than clothing fabrics. Common examples of these materials are Manila hemp (abaca) and sisal, both of which are used for twines and ropes worldwide. In addition, abaca and sisal have been both used historically for paper fibers (Timothy and Michael, 1997). According to Alexander et al. (2005), abaca and sisal are hard fibers obtained from the leaves of their plant and they are considered to be the strongest of all plant fibers.

Whereas the leaf fiber strands display the characteristically long length of bast fibers, the ultimate fibers comprising these strands are typically less than 12 mm long as shown in Table 2.2. Like most of the plant fibers, the leaf ultimate fibers have typical diameters of approximately 30 mm.

Table 2.2: Dimensions of leaf fibers (Timothy and Michael, 1997).

Type	Property	Abaca	Henequen	Phormium	Palm	Sisal
Strand	Length (cm)	365	60-150	150-240	30-60	60-120
	Width (mm)	0.2-1	0.1-0.5	0.1-0.5	0.15-0.25	0.1-0.5
Ultimate	Length (mm)	2-12	1.5-4	2-11	-	0.8-7
	Width (mm)	6-40	8.3-33	5.25	18	8-48

2.3.3 Seed-hair fibers

Unlike the bast and leaf fibers, seed-hair fibers are single celled. These fibers are attached to the seeds of certain plants for aid in wind-dispersal (Timothy and Michael, 1997). One exception to this is coir, a fiber produced from the husk of coconuts. Like bast fibers, coir is produced by separation technique after husks undergo retting. Coir can produce long fiber strands, depending on the production process. The ultimate coir fibers are quite small which are less than 1 mm long and 6 mm in diameter as shown in Table 2.3.

The more typical seed-hair fibers are all similar in morphology to cotton, with long lengths (20 mm) and small diameters (20 mm). Cotton fibers consist of the unicellular seed hairs of the bolls of the cotton plant (Alexander et al., 2005). Innumerable products are made from cotton, primarily textile and yarn goods, cordage and automobile tire cords. Cotton fibers are the backbone of the textile trade of the world. Short fibers that are left on the seed after processing are termed linters (Timothy and Michael, 1997). Cotton linters are commercially available and are currently use as rag content in fine papers. These waste fibers have similar diameters to the textile cotton, with much shorter lengths (less than 7 mm). Kapok and milkweed both have thin cell walls and large diameter lumens. Since kapok is difficult to spin, it is primarily used as loose fill for buoyancy or insulation purposes. Milkweed has been used only on a limited basis for fill; however, it has been studied for its papermaking and textile spinning qualities (Timothy and Michael, 1997).

Table 2.3: Seed-hair fiber dimensions (Timothy and Michael, 1997).

Property	Coir	Cotton	Cotton linters	Kapok	Milkweed
Length (mm)	0.2-1	10-50	3-7	15-30	5-40
Diameter (mm)	6.24	12-25	30	10-30	6-38

2.3.4 Cereal straws

Straw is produced throughout the world in enormous quantities as a by-product of cereal cultivation. Half the straw is simply burned on the fields just to get rid of it or else it is buried in greater quantities than what is needed to replenish organic matter in the soil (Alexander et al., 2005). Historically, straws from wheat, rye, and rice were widely used as a pulp source for paper-making. Whereas this practice became extinct in North America and much of Europe by 1960, it is still practiced in southern and eastern Europe as well as many Asian, Mid-Eastern, and Southern American countries. Although corn stalks are widely available and have been studied as a pulp source, their commercial use has been limited (Timothy and Michael, 1997; Foyle et al., 2007).

According to Alexander et al. (2005), straw consists of stem and leaves branching off the stem at the nodes. Straw also was found to have less cellulose and lignin but more hemicelluloses as compared to wood. In general, wheat straw and corn stalk fibers have small diameters and average lengths producing a favorable aspect ratio of 110 as shown in Table 2.4. Fibers from rice straws typically have smaller diameters (5 to 14 mm) with a long aspect ratio of 170 (Timothy and Michael, 1997). Straw offers some technological advantages over wood because it allows better packing of the fibers or strands and the degree of bonding between them is much better.

Table 2.4: Cereal straw fiber dimensions (Timothy and Michael, 1997).

Property	General	Corn	Rice	Wheat
Length (mm)	0.68-3.12	1.0-1.5	0.65-3.48	1.5
Diameter (mm)	7-24	20	5-14	15

2.3.5 Grass fibers

Many other grasses have been and are considered as a fiber source. Because of limited availability or processing difficulties, most of these fibers (except sugarcane bagasse) have never become widely used; however, they are often common in certain localities. These fibers (Table 2.5) include sugarcane bagasse, bamboo, esparto, and sabai grass.

In these grass fibers, sugarcane bagasse is the most common and widely studied among the researchers. Sugarcane is grown as a source of sucrose in many tropical and sub-tropical countries on many continents. Bagasse is the residue remaining after the sugar has been extracted (Timothy and Michael, 1997). Currently, this material is used for paper in India and Mexico and in boilers to generate process steam for the sugar production. Paper and material fiber provide the more economical use for this material (Timothy and Michael, 1997). The bagasse consists of pith and rind materials. The rind consists of 50% of the dry bagasse weight and contains most of the usable fiber. In general, these fibers are similar to hardwood fibers average 2.8 mm in length and 34 mm in diameter, producing and aspect ratio of 82. Two grasses, esparto and sabai, are widely available in North Africa and India, respectively. Both grasses are locally common as a paper fiber, with sabai at one time comprising 20% of the pulped material in India. Compared to softwood fibers, these grass fibers have small diameters (9 mm) and average lengths (1-2 mm), producing fibers with large aspect ratios between 100 and 200 (Timothy and Michael, 1997).

Table 2.5: Other grass fiber dimensions (Timothy and Michael, 1997).

Property	Sugarcane bagasse	Bamboo	Esparto	Sabai
Length (mm)	2.8	2.7-4	1.1	0.5-4.9
Width (mm)	34.1	15	9	9-16

2.4 Main components of natural fibers

The major chemical component of a living tree is water, but on a dry weight basis, all plant cell walls consist mainly of sugar-based polymer (carbohydrates) that are combined with lignin with lesser amounts of extractives, protein, starch and inorganics (James and Jeffrey, 1997). The chemical components are distributed throughout the cell wall, which is composed of primary and secondary wall layers. Chemical composition varies from plant to plant, and within different geographic locations, ages, climate and soil conditions (James and Jeffrey, 1997). According to Sain and Panthapulakkal (2004), the age of the plant, climatic conditions and fiber processing techniques influence the structure of fibers as well as their chemical composition. Bledzki and Gassan (1999) summarized that component or composition means values of plant fibers such as cellulose, hemicellulose, lignin, pectin, waxes and water soluble substances, which cellulose, hemicellulose and lignin are the major components with regard to the physical properties of the fibers. The percentages and properties of the components contribute to the overall properties of the fibers (Sain and Panthapulakkal, 2004).

2.4.1 Cellulose

Cellulose is the essential component of all plant fibers and is the most abundant organic chemical on the face of the earth. In 1838, Anselme Payen suggested that the cell walls of large numbers of plants consist of the same substance, to which he gave the name "cellulose" (Bledzki and Gassan, 1999).

According to Nishino (2004), cellulose is a natural linear homopolymer (polysaccharide), in which D-glucopyranose rings are connected to each other with β-(1-4)-glycosidic linkages. It is thus a 1,4-β-D-glucan (Bledzki and Gassan, 1999). Sain

and Panthapulakkal (2004) summarized that the basic chemical structure of cellulose in all plant fibers is the same whereas the cell geometry of each type of cellulose varies with the fiber; this is one of the factors which contribute to the mechanical properties of the green fibers. The molecular structure of cellulose can be seen from Figure 2.6 (Edwards et al., 1997). It can be seen that cellulose structure contained alcoholic hydroxyl group. These hydroxyl groups form intermolecular and intra molecular hydrogen bonds with the macromolecule itself and also with other cellulose macromolecules. Therefore, all natural fibers are hydrophilic in nature (Mohanty et al., 2005; Herrera and Valadez, 2005).
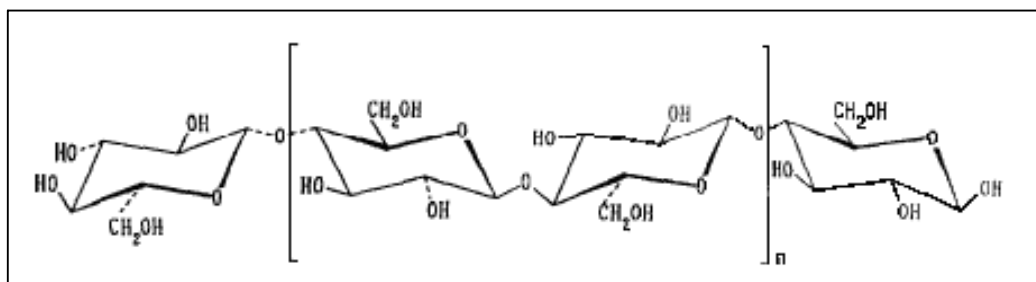

Figure 2.6: Molecular structure of cellulose (Edwards et al., 1997).

Although the chemical structure of cellulose from different natural fibers is the same, the degree of polymerization (DP) varies. The mechanical properties of a fiber are significantly dependent on the DP (Mohanty et al., 2005). According to James and Jeffrey (1997), the number of glucose units in a cellulose molecule is referred to as the degree of polymerization (DP), and the average DP for plant cellulose ranges from a low of about 50 for a sulfite pulp to approximately 600, depending on the determination method used.

As the packing density of cellulose increases, crystalline regions are formed. Most plant-derived cellulose is highly crystalline and may contain as much as 80 % crystalline regions. The remaining portion has a lower pacing density and is referred to as amorphous cellulose. On a dry weight basis, most plants consist of approximately 45-50 % cellulose. This can vary from a high (cotton) of almost 90 % to a low about 30 % for stalk fibers (James and Jeffrey, 1997).

2.4.2 Hemicelluloses

Hemicelluloses are another component of plant fibers. Hemicelluloses are polysaccharides composed of a combination of 5- and 6-ring carbon ring sugars (Alexander et al., 2005). Figure 2.7 shows partial structure of hemicelluloses with a combination of 5-ring carbon ring sugars (Bledzki and Gassan, 1999).
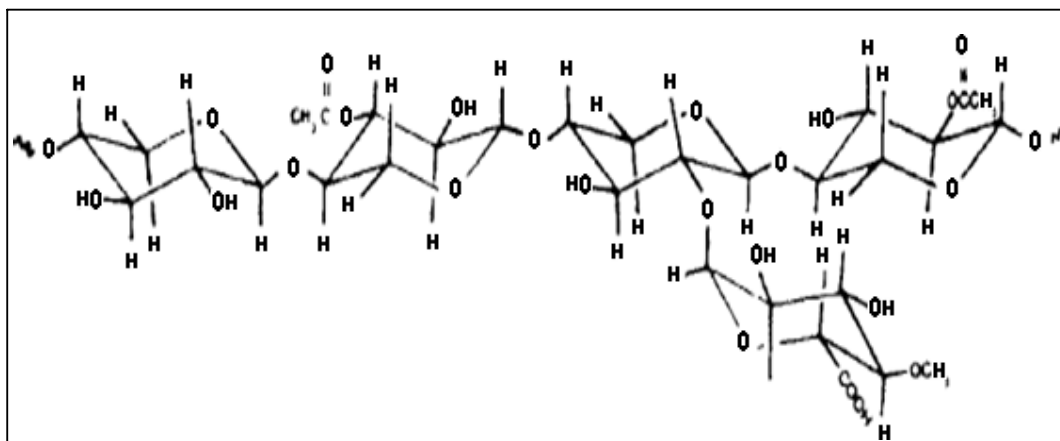

Figure 2.7: Partial structure of hemicelluloses (Bledzki and Gassan, 1999).

Hemicelluloses has a random, amorphous structure with little strength, highly branched polymer compared to the linearity of cellulose, and has a degree of polymerization lower than that of cellulose (Sain and Panthapulakkal, 2004; Hemicelluloses, 2007). They are also classically defined as alkali soluble material after

removal of pectic substances, very hydrophilic and easily hydrolyzed in acids (Xiao et al, 2001; Alexander et al., 2005).

Unlike cellulose, which contains only a 1, 4-β-glucopyranose ring, hemicellulose contains different types of sugar units such as D-xylopyranose, D-glucopyranose, D-galactopyranose, L-arabinofuranose, D-mannopyranose, and D-glucopyranosyluronic acid with minor amount of other sugars (James and Jeffrey, 1997). These monomers of hemicelluloses are shown in Figure 2.8. Usually, all of the monomers are present. There may even be small amounts of L- sugars but Xylose is always the sugar present in the largest amount (Hemicelluloses, 2007).
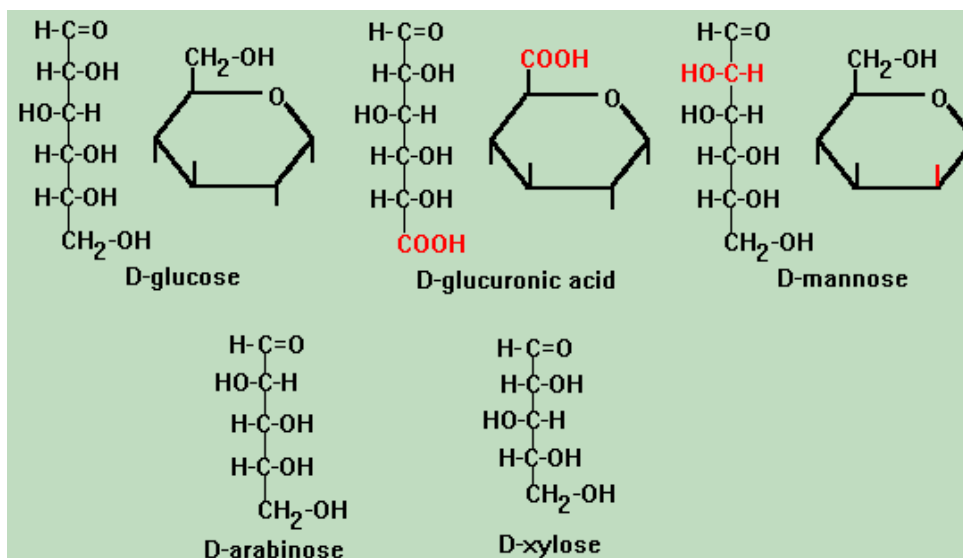

Figure 2.8: Monomers of hemicelluloses (Hemicelluloses, 2007).

Bledzki and Gassan (1999) have concluded that hemicelluloses differ from cellulose in three aspects. First, it contains several different sugar units whereas cellulose contains only 1, 4-β-D-glucopyranose units. Second, it exhibits a considerable degree of chain branching, whereas cellulose is a linear polymer. Third, the degree of polymerization of native cellulose is 10-100 times higher than that of hemicelluloses.

2.4.3 Lignin

Lignin is a complex chemical compound most commonly derived from wood and an integral part of the cell walls of plants. The term was introduced in 1819 by de Candolle and is derived from the Latin word *lignum*, meaning wood (Lignin, 2007). Lignin is the compound that gives rigidity to the plants. It is thought to be a complex, three-dimensional copolymer of aliphatic and aromatic constituents with very high molecular weight. Lignin is amorphous and hydrophobic in nature (Alexander et al., 2005; Mohanty et al., 2005; James and Jeffrey, 1997). The partial structure of lignin can be seen in Figure 2.9.
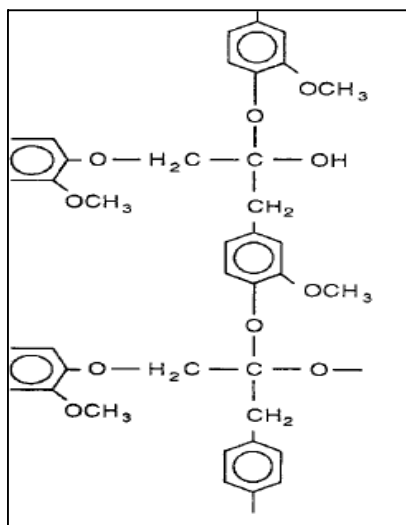

Figure 2.9: Partial structure of lignin (Bledzki and Gassan, 1999).

Lignin can be classified in several ways but they are usually divided according to their structural elements. All plants lignin consist mainly of three basis building blocks of guaiacyl, syringyl, and p-hydroxyphenyl moieties, although other aromatic type units also exist in many different types of plants, which forms a randomized structure in a tri-dimensional network inside the cell walls (Xiao et al., 2001; James and Jeffrey, 1997).

Figure 2.10 shows building blocks of lignin. There is a wide variation of structure within different plant species. The function of the lignin in plants is as an encrusting agent in the cellulose/hemicelluloses matrix or called plant cell wall adhesive. Therefore, lignin acts as a structural support material in plants by filling the spaces between the polysaccharide fibers, which hold the natural structure of the plant cell walls together (Sain and Panthapulakkal, 2004; James and Jeffrey, 1997). Lignin stiffens the cell walls and acts as a protective barrier for the cellulose, thus the carbohydrate is protected from chemical and physical damage. They are totally insoluble in most solvents and cannot be broken down to monomeric units. The properties of lignin vary with the fiber type, but it always has the same basic composition (Mohanty et al., 2005; Sain and Panthapulakkal, 2004).
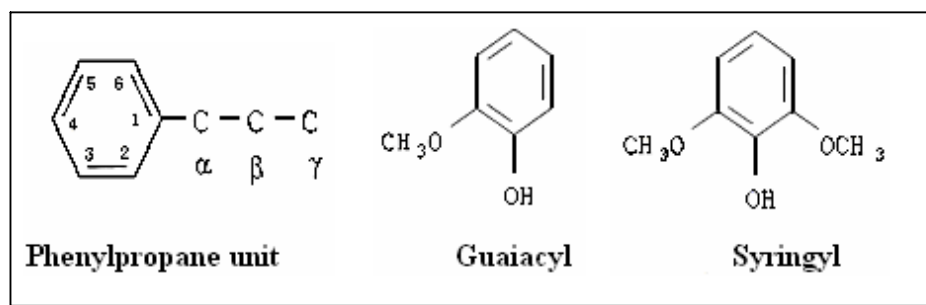

Figure 2.10: Building blocks of lignin (James and Jeffrey, 1997).

Lignin plays a crucial part in conducting water in plant stems. The polysaccharide components of plant cell walls are highly hydrophilic and thus permeable to water, whereas lignin is more hydrophobic. The crosslinking of polysaccharides by lignin is an obstacle for water absorption to the cell wall. Thus, lignin makes it possible for the plant's vascular tissue to conduct water efficiently (Lignin, 2007).