PROPERTIES OF HYBRID PLYWOOD FROM OIL PALM TRUNK (OPT) VENEER AND EMPTY FRUIT BUNCHES (EFB) MAT

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by

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LIST OF ABBREVIATES

UF	Urea formaldehyde
PF	Phenol formaldehyde
OPEFB	Oil palm empty fruit bunches
OPT	Oil palm trunk
SEM	Scanning electron microscopy
TGA	Thermogravimetric analysis
MDF	Medium density fiberboard
OH	Hydroxyl
OSB	Oriented strand board
LVL	Laminated veneer lumber
WBP	Water boil proof
INT	Interior
FESEM	Field emission scanning electron microscope
OPF	Oil palm frond
FFB	Fresh fruit bunch

SIFAT-SIFAT PAPAN LAPIS HIBRID DARIPADA VENIR BATANG DAN HAMPARAN TANDAN KOSONG BUAH KELAPA SAWIT

ABSTRAK

Kekurangan kayu sebagai sumber bahan mentah telah memaksa industri berasaskan kayu untuk mencari alternatif kepada bahan mentah tempatan dan biojisim kelapa sawit adalah alternatif yang paling sesuai. Kajian ini adalah berasaskan kajian untuk menukar batang kelapa sawit dan tandan kosong kelapa sawit kepada papan lapis baru dan menganalisa kekuatannya. Lima lapis papan lapis hibrid (venir batang kelapa sawit dan hamparan tandan kosong kelapa sawit disusun secara berselang-seli) dengan menggunakan resin yang berbeza (fenol formaldehid dan urea formaldehid) serta tahap sapuan perekat yang berbeza (300 g/m^2 and 500 g/m^2) telah disediakan. Kekuatan mekanikal, fizikal dan termal papan lapis telah dikaji. Kekuatan mekanikal seperti kekuatan lenturan, modulus lenturan dan pengeluaran skru untuk papan lapis hibrid menunjukkan kekuatan mekanikal yang lebih baik berbanding papan lapis batang kelapa sawit. Papan lapis yang menggunakan fenol formaldehid menunjukkan sifat-sifat yang lebih baik berbanding papan lapis menggunakan urea formaldehid. Pengembangan ketebalan dan penyerapan air papan lapis batang kelapa sawit adalah lebih tinggi berbanding papan lapis hibrid. Pengembangan ketebalan dan penyerapan air papan lapis yang menggunakan fenol formaldehid adalah lebih baik berbanding papan lapis menggunakan urea formaldehid. Kekuatan termal papan lapis dikaji dengan menggunakan analisis termogravimetrik (TGA). Panel yang disapu fenol formaldehid dengan sapuan perekat 500 g/m^2 menunjukkan kestabilan termal lebih baik berbanding panel lain. Ujian delaminat menunjukkan sampel papan lapis hibrid dengan sapuan perekat 300 g/m^2 menggunakan resin urea

formaldehid memberikan delaminat tertinggi, manakala sampel yang diperbuat dari fenol formaldehid menunjukkan tiada delaminat. Mikroskopi elektron imbasan (SEM) digunakan untuk mengkaji ikatan gentian matrik dan permukaan morfologi papan lapis menggunakan tahap sapuan perekat yang berbeza. Ikatan fiber-matriks menunjukkan peningkatan yang baik untuk panel yang menggunakan resin dengan sapuan perekat 500 g/m^2 untuk kedua-dua resin.

PROPERTIES OF HYBRID PLYWOOD FROM OIL PALM TRUNK (OPT) VENEER AND EMPTY FRUIT BUNCHES (EFB) MAT

ABSTRACT

Shortage of wood as a raw material has coerced wood based industries to find alternative local raw materials, and oil palm biomass appears as the most viable alternative. This work was based on the studies of converting oil palm trunk (OPT) and oil palm empty fruit bunches (OPEFB) into new plywood and to analyze their properties. Five-ply hybrid plywood (oil palm trunk veneer and empty fruit bunch mat was arranged alternately) with different spread levels (300 g/cm^2 and 500 g/m^2) of resins (phenol formaldehyde and urea formaldehyde) were prepared. The mechanical, physical and thermal properties of the plywood were studied. The mechanical properties, such as bending strength, bending modulus and screw withdrawal of hybrid plywood showed better mechanical properties than oil palm trunk plywood. Plywood made using phenol formaldehyde showed better properties compared to plywood made using urea formaldehyde. The swelling thickness and water absorption of oil palm trunk plywood were higher than that of hybrid plywood. The swelling thickness and water absorption of the plywood made using phenol formaldehyde were better than that of plywood made using urea formaldehyde. The thermal properties of the plywood panels were determined through thermogravimetric analysis (TGA). The panels glued with phenol formaldehyde with a spread level of 500 g/m^2 showed better thermal stability as compared to the other panels. The delamination test showed that the samples of hybrid plywood with glue spread 300 g/m^2 using urea formaldehyde exhibited the highest delamination while plywood made using phenol formaldehyde samples showed no delamination. Scanning electron microscopy

(SEM) was used to study the fiber matrix bonding and surface morphology of the plywood using different glue spread levels of the resins. The fiber-matrix bonding showed good improvement for the panel glued with 500 g/m^2 for both resins.

CHAPTER 1

INTRODUCTION

1.1 General

The oil palm (*Elaeis guineensis* Jacq.) originated from West Africa and it spread throughout the tropics and is now grown in 16 or more countries (Mohd Basri *et al*., 2004). Malaysia currently accounts for 41 % of world palm oil production and 47% of world exports, and therefore also for 11% and 25% of the world's total production and exports of oils and fats respectively (MPOC, 2009). The year 2009 was a challenging one for the Malaysian palm oil industry amid the lingering effects of a weak global economy and issues on sustainability and environment associated with oil palm cultivation. Nevertheless, the industry still remains resilient, recording a satisfactory performance with exports of oil palm products rising by 2.9%, although export earnings declined by 24.0% to reach RM 49.6 billion because of the relatively lower oil palm product prices traded in 2009 (Mohd Basri, 2010).

The oil palm is one of the most important crops in Malaysia. It produces palm oil and palm kernel oil, which are widely used in food and other industries such as detergents and cosmetics. The total oil palm planted area in the country increased by 4.5% to 4.69 million hectares in 2009. Among the regions, Sarawak registered the largest increase in planted area with a growth of 12.8%, followed by Peninsular Malaysia 3.3% and Sabah 2.1%. Sabah is still the largest oil palm planted State, accounting for 1.36 million hectares or 29% of the total planted area in the country (Mohd Basri, 2010).

The residue biomass consists of huge amount of lignocellulosic materials such as oil palm fronds, trunks and empty fruit bunches. The projection figures of these residues are as follows: 7.0 million tonnes of oil palm trunks, 26.2 million tonnes of oil palm fronds, and 23% of oil palm empty fruit bunch (OPEFB) per tonne of fresh fruit bunch (FFB) processed in oil palm mill (Saleh and Puad, 2003). These have potential to be used as raw materials in the wood-based industries. As for example, the annual availability of oil palm trunks is estimated to be 13.6 million logs based on 100,000 ha of replanting per year (Anis *et al.*, 2005). On the other hand, biomass from the oil palm industry has been gaining commercial importance for the past 10 years. It generates a large amount of residues and is the number one source for natural fibers. Extensive research on the conversion of oil palm trunks, OPEFB and fronds into value added products such as particleboard, MDF, cement bonded particleboard, fiber reinforced plastics and plywood has been initiated with great commercial potentials (Zaidon *et al*., 2007).

In the wood based industry, the shortage of wood as a raw material has become eminent recently. The world demand for plywood and round wood is expected to increase at a rate of about 1.0% up to 2030, and this indicated that there would be shortage of wood raw materials in the near future (Anis *et al.*, 2005). This is also due to many manufacturing units that produce wood based products especially plywood and lumber having closed down. Recently the wood based industry faces problem of raw materials supply, not only from the natural forests, but from rubber plantations as well. It was estimated that wood based industry utilize at least 20 million solid wood annually. Therefore, there is a need to find alternative source for local raw materials, and oil palm biomass appears to be the most viable alternative source of raw materials, especially the oil palm trunk, which is possible to be utilized as value added product as well as future wood-based industry (Mohamad *et al*., 2005).

Agro-wastes have attracted worldwide attention as a potential reinforcement for the composites because of their viability, easy to process, light weight, non hazardous, recyclable, bio friendly characteristics. In addition, utilization of biomass in lignocellulosic composites leads to several advantages such as low density, greater deformability, less abrasiveness to equipment, biodegradability and low cost (Arib *et al*., 2004; Abdul Khalil *et al.*, 2008). Generally, oil palm has an economical life span of about 25 years. Related to the large production of main products from oil palm in Malaysia, the abundance of oil palm trunks should be utilized. A large quantity of cellulosic raw material is generated in the form of felled trunks and fronds during replanting. In Malaysia, the oil palm plantation covering an area of approximately 4.69 million hectares (Mohd Basri, 2010) will generate large quality of residues in the form of trunks, fronds and OPEFB, which can be considered as alternative materials for the wood based industry.

The motivation of using oil palm (*Elaeis guineensis*) stems or trunks as plywood was initiated due to the difficulty in obtaining good quality timber as well as the abundance of oil palm trunks in Malaysia. Up to now, there is no economical value of oil palm trunk from structural point of view and ultimately it becomes a hazardous material to farmers. For non-structural applications, efforts are made to look into the possibilities of using the trunks as furniture and particleboard raw material (Chew *et al.*, 1985). Generally, they are regarded as inferior raw materials compared to solid wood in terms of strength characteristics. However, recent studies specify that oil palm trunk can be exploited as structural components if proper sampling, grading and drying are made (Anon., 2002).

1.2 Objectives

Studies on hybrid plywood using oil palm biomass are still new and no research has been published yet. Therefore, an attempt was undertaken by our research group to understand the mechanical, physical and thermal properties of hybrid plywood. The main objectives of this research are summarized below:

1. To produce hybrid plywood from oil palm trunks and oil palm empty fruit bunches.
2. To study the physical, mechanical and thermal properties of oil palm trunk plywood and hybrid plywood.
3. To study the effects of using different levels of glue spread (500 g/m^2 and 300 g/m^2) with different types of adhesives (urea formaldehyde and phenol formaldehyde) to the oil palm trunk plywood and hybrid plywood.

1.3 Justification

The reason this composite was named hybrid plywood because it uses two raw materials which are oil palm trunk and oil palm empty fruit bunches. Oil palm trunk veneer is hybridized with oil palm empty fruit bunches mat to produce hybrid plywood. It was called plywood because the arrangement of these composites based on the theory of plywood. The oil palm veneer and empty fruit bunches were arranged alternately and the oil palm trunk veneer was arranged in different direction. Besides, all the testing used followed the British Standard of plywood.

The raw material used in this study was oil palm trunk (OPT) and oil palm empty fruit bunches (OPEFB), which was chosen because its commercial value has not been exploited and its utilization only started recently and it is believed that it can be considered as an alternative material for wood based industry. Both of these raw materials are wastes and abundance in Malaysia. Therefore, the abundance of oil palm trunks and empty fruit bunches should be utilized.

To take full advantage of the oil palm trunks and oil palm empty fruit bunches, both can be combined in the same matrix to produce hybrid composites, and thereby an economically viable composite can be obtained. Literature survey showed that there has been no report on the properties of hybrid plywood made of OPT and OPEFB. The lack of effort in utilizing waste from the oil palm industry as hybrid plywood, instill my interest to conduct the present research.

CHAPTER 2

LITERATURE REVIEW

2.1 The Oil Palm

2.1.1 Introduction

Elaeis guineensis Jacq., commonly known as the oil palm, is the most important species in the genus *Elaeis,* and belongs to the family Palmae. The oil palm is an erect monoecious plant that produces separate male and female inflorescences (Teoh, 2002). The oil palm trees are shown in Figure 2.1.

Figure 2.1 Oil palm trees (GRAIN, 2007)

The Malaysian oil palm industry started in 1917 and grew slowly until the late 1950s due to switch over from rubber to oil palm during agricultural diversification policy. From then onwards, the industry started to grow rapidly, and currently, very little room remains for any significant increase in oil palm plantations in Peninsular Malaysia. As such, all future growth was expected to be in Sabah and Sarawak. Despite this enormous production, the oil is only a minor fraction of the total biomass produced in the plantation. The remainder consists of a huge amount of lignocellulosic materials in the form of fronds, trunks and empty fruit bunches. The year 1985 was considered as the start of a major replanting era in the oil palm industry, and from 1985 to 1995, there was a steady increase in oil palm replanting. By 1997, the replanting era reached its maximum, yielding over 27 million tonnes of biomass. As such, the oil palm industry must be prepared to take advantage of the situation and utilize the available biomass in the best possible manner (Yusof, 2007).

Oil palm is produced in 42 countries worldwide and area wise occupied approximately 27 million acres. Production has nearly doubled in the last decade, and oil palm has been the world's first fruit crop in terms of production since 20 years. Recently, the oil palm total area under cultivation is about 3.5 million hectares, while total palm oil production for the year 2001 was 11.8 million tonnes. The total planted area increased to about 3.87 million hectares in 2004 (Mohamad *et.al*, 2005; Abdul Khalil *et al.* 2008).

The current status of oil palm biomass in Malaysia during the year 2006 as stated by Anis *et al.* (2007) showed that the total area of oil palm trees planted was 4.17 million hectares. Sumathi *et al.* (2008) stated that oil palm mills generally generate large amount of biomass wastes. The amount of biomass produced by an oil palm tree, include oil and lignocellulosic materials an average of 231.5 kg dry weight/year. In the year 2008, OPEFB and OPT are the major contributor of oil palm biomass, whereby about 15.8 and 8.2 million tonnes, respectively, have been produced annually.

Composites such as plywood block board and fibreboard can be produced from the parts of oil palm trunk. Besides the trunks, fronds and OPEFB can be used as raw material for one and three-layered particleboard, bonded with resin. The denser material from the base of the trunk can be used to make furniture after treatment with suitable resin. Several of these uses have been tested successfully, in the sense that usable materials have been produced (Koh *et al*., 1999).

2.1.2 Oil palm trunk (OPT)

Oil palm is replanted at an average age of 25 years. Palms that are still producing high yield, but have grown too tall for harvesting, can be considered ready for replanting irrespective of their ages. The trunks are normally left to rot or burnt down in the field during replanting process. However, freshly felled trunks cannot be easily burnt in the field because of the high moisture content. Leaving the trunks in the field without further processing will physically hinder the process of replanting (Mohamad *et al.*, 1985).

Smaller chip sizes of oil palm trunk rapidly decompose thus disposing the trunk waste better. Oil palm trunks contain very high moisture content (between 60-300 %) depending on the height and age of the trunk. The trunk consists of lignocellulosic material which is a valuable raw material for the value added products (Wan Asma and Wan Rasidah, 2007).

Oil palm trunk is largely composed of parenchymatous tissues with numerous fibrous strands and vascular bundles. The tough vascular bundles are scattered in soft parenchyma tissue. Unlike coconut, the oil palm trunk is not homogenous in nature. The parenchymatous tissues are soft and contain mainly short chain polysaccharides and starch. The fibrous strands, on the other hand, are mainly hard cellulose, which is difficult to degrade. One of the earliest data reported that the weight ratio of the parenchymatous tissue to the fiber strands is about 24-29 % to 71-76 %. The parenchyma is rich in starch, containing about 55 % compared to 2.4 % in the fiber. However, the lignin content is quite similar, that is 15.7 % in parenchyma and 20 % in fiber (Wan Asma and Wan Rasidah, 2007).

The advantages of oil palm trunk is in the forms of optimized performance, minimized weight and volume, cost effectiveness, fatigue and chemical resistance, controlled bio degradability and environmental considerations. "New wood-lumber" is formed by combining oil palm trunk with other materials available. Many agro-wastes are being combined with other lignocellulosic materials, metals, plastics, glass and synthetic fibers, and the properties of these composites are still studied (Hill *et al.*, 1998). Figure 2.2 below shows an oil palm trunk.

Figure 2.2 Oil palm trunk

A fundamental research demonstrated that oil palm trunk could be engineered into a palm 'wood' or solid oil palm trunk; however, the results have not been promising. Kiln dry methods resulted in a high degree of shrinkage, checks, warping, twisting and collapse with low recovery, expensive cost processing and difficult to dry. New oil palm trunk exhibit superior and good permeability through modification with microwave technique as compared to kiln dry treatment. Artificial wood lumber is a structural composite, thermoset matrices combined with modified solid oil palm trunk using the impregnation process. The advantages of using thermosets resin are low viscosity, low volatility, good polymerization completion, less heat generation at polymerization, and low price (Drzal and Madhukar, 1993; Anis *et al*., 2005).

The modified oil palm trunk acts as reinforcement in the polymer matrix which improves the strength, stiffness, hardness, wear proof properties, mechanical, physical, dimensional stability, chemical resistant properties, decay and surface beauty compared to ordinary wooden lumber (Abdul Khalil *et al.*, 2010). There are wide range of applications of oil palm trunk in industry, transportation, home and recreation. Specific product areas include wall panels, sub floors, roof panels, doors, furniture parts and specialized containers.

Most of the oil palm trunk is converted into various types of wood such as sawn wood and plywood or lumber. Oil palm lumber has been successfully utilized as core in the production of blackboard. The sawn wood produced from oil palm trunk can be used to make furniture but not for building structure due to its low specific density. However, the strength of the plywood produced from oil palm trunk was found to be comparable with commercial plywood (Sumathi *et al.*, 2008). The shells are usually used to cover the surface of the roads in the plantation area. Oil palm trunk also has been used to produce particleboards with chemical binders. Moreover, some of the trunks are mixed with OPEFB and oil palm fibers to be combusted and produce energy (Sumathi *et al.*, 2008).

With the decreasing supply of raw materials from traditional sources such as rubber wood and tropical hardwoods, utilization of OPT as an alternative lignocellulosic raw material for wood based industry is crucial. The shortage of raw material will lead to a difficult situation to maintain the current production level in wood based industry. However, the main obstacle of utilization of OPT is due to the plant being a monocotyledon and is not really a wood, as what the wood-based industry have been used to. Considering to the physical and mechanical properties of OPT, one is dealing with a material which is made up of parenchyma and vascular bundles. Fibers that are supposed to make up the strength are less and irregular in characteristics as compared to the dicotyledonous wood (Hashim *et al.*, 2006).

Several advantages of utilization of OPT veneer as compared to solid sawn OPT timber for conversion into various products (Hashim *et al.*, 2006) are as follows:

i. The percentage of veneer recovery is much higher than solid OPT sawn timber. With the latest technology, the peeling of OPT can be carried out easily and efficiently on a smaller size diameter, which lead to optimize utilization of most parts of the trunk.
ii. Cost of production of veneer is lower. The recovery rate is expected to decrease after the drying and sorting process.
iii. OPT veneer dries faster than sawn OPT timber although it has high moisture content.
iv. On the average, the strength properties of OPT plywood are better and variation is significantly lower than sawn OPT timber.

However, the natural characteristics of OPT are the main challenges in making it to be a manageable raw material for producing plywood.

i. The freshly cut OPT is very prone to fungal and insect infestation.
ii. OPT easily degrades when being left without proper treatment after felling.
iii. OPT has high moisture content and enormous variation in density.
iv. The OPT becomes spongy near to the core due to the anatomical characteristics.
v. The OPT is inconsistent in its physical characteristics.

vi. The knife used to cut OPT becomes easily blunt due to the presence of the silica in OPT.

vii. The OPT veneer absorbs more adhesives as compared to tropical hardwoods because of the rough surfaces.

2.1.3 Oil palm empty fruit bunches (OPEFB)

Recently, utilization of biomass resources has been the subject of various studies. Among the other oil palm fiber residues, OPEFB offers the best prospect for commercial exploitation since it is readily available at the palm oil mill which can minimize transportation and procurement costs. In Malaysia, OPEFB is one of the biomass materials, which is a by-product from the palm oil industry. The production of OPEFB in 2002 was estimated to be around 5.2 million tonnes per year (Kwei *et al.*, 2007). OPEFB is the residual bunch after removal of the fruits; it constitutes 20 % to 22 % of the weight of the fresh fruit bunches.

The main constituents of the lignocellulose are 65 % holocellulose and 25 % lignin. Many studies have been carried out on the utilization of the OPEFB such as in particleboard, pulp, medium density fiberboard, and composites (Rozman *et al.*, 2001; Rozman *et al.*, 2004). At present, OPEFB is seldom burnt as fuel as the shell and fruit fiber is sufficient for the oil palm mill. But most of the EFB are disposed off at the oil palm plantation or burned at the mills to produce OPEFB ash. Thus, finding useful utilization of the OPEFB will surely alleviate environmental problems related to the disposal of oil palm wastes. The oil palm empty fruit bunches is shown in Figure 2.3.

Figure 2.3 Oil palm empty fruit bunches (Tanaka, 2003)

In recent times, OPEFB has been investigated as a raw material for building materials and more OPEFB are now used for other value-added products like pulp, medium density board, wood composite product and fiberboard. In general, utilization of biomass in lignocellulosic composites has been attributed to several advantages such as having low density, greater deformability, less abrasiveness to equipment, biodegradability and low cost (Chan, 1999; Rozman *et al.*, 2004).

This OPEFB has high cellulose content and has potential as natural fiber resources, but their applications account for a small percentage of the total biomass productions. Several studies showed that OPEFB of oil palm with the average of cellulose content of 49-65 % has the potential to be an effective reinforcement in thermoplastics and thermosetting materials but the utilization of OPEFB fibers can be limited in the industrial applications due to the some well-known drawbacks that may lead to composites with poor properties (Sreekala *et al.*, 2001; Myrtha *et al.*, 2008).

2.2 Chemical Compositions of Oil Palm Fiber

Plant fibers are a composite materials designed by nature and the fibers are basically a rigid, crystalline cellulose microfibrils-reinforced amorphous lignin with hemicelluloses matrix. These fibers are lignocellulosics that are three-dimensional composites, principally composed of macromolecules of cellulose, hemicelluloses, and lignin. The three dimension polymeric components, which occur in the cell wall of lignocellulosics, determine most of the properties of lignocellulosics (Ndazi *et al.*, 2006; Saira *et al.,* 2007).

Pectin is a collective name for heteropolysaccharides, which consist essentially of polygalacturon acid. Pectin is soluble in water only after a partial neutralization with ammonium hydroxide or other alkali. Waxes and water soluble substances are also found in small amounts in the cell wall of a lignocellulose fiber. The chemical compositions of a lignocellulose fiber vary according to the species, growing conditions, method of fiber preparations and many other factors (Bledzki *et al.*, 1999). Chemical compositions of oil palm fibers are shown in Table 2.1.

Table 2.1 Oil palm fiber chemical compositions (Mohamad *et al.*, 1985; Sreekala *et al.*, 2001)

Chemical composition (%)					
	Extractive	**Holocellulose**	**Cellulose**	**Lignin**	**Ash**
Oil palm empty fruit bunches	4.1	65	49-65	25	2-3.5
Oil palm trunk	9.8	45	29	18	2.3

2.2.1 Cellulose

Cellulose is the main component in lignocellulose fibers and is the reinforcing material within the cell wall. Cellulose is composed of β-D-glucopyranose monomeric units held together by β-1, 4-glycosidic bonds that are alternately inverted to form cellubiose dimeric units as shown in Figure 2.4. This results in the cellulose backbone being linear and cellubiose units link together via glycosidic linkages to form the polymer cellulose (Hill, 2006).

Cellulose is a high molecular weight homopolymer of glucose and a number of cellulose chains are closely associated with extensive hydrogen bonding networks to form the microfibril that produces a strong crystalline structure and as reinforce element in the cell wall (Hill, 2006). The microfibrils have associated with the crystalline and amorphous components with associated OH groups. Because of the highly crystalline nature of the microfibrils, the cellulose component is relatively unreactive and thermally stable (Hill, 2006).

According to Bledzki *et al.* (1999), cellulose can be characterized as cellulose I, cellulose II, cellulose III and cellulose IV, based upon their physical crystal structures. Furthermore, the mechanical properties of lignocellulose fibers depend on the type of cellulose whether it is cellulose I or cellulose II because each type of cellulose has its own geometrical condition, which influences the mechanical properties. Seena *et al.* (2002) reported that the elongation at break value of banana fiber is higher compared to glass fiber because the cellulose fiber is found to have higher extensibility compared to fiber glass.

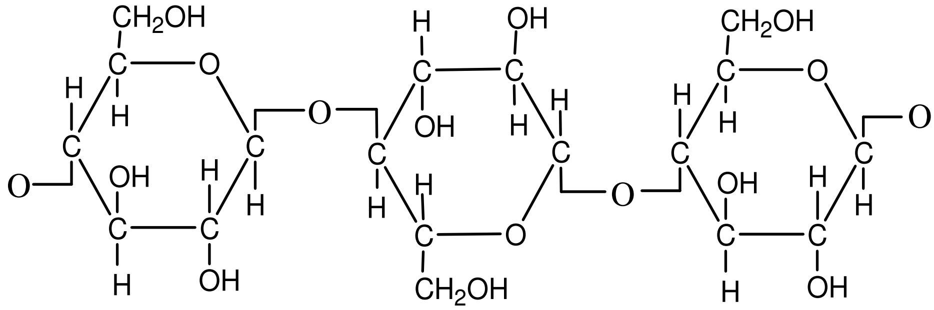

Figure 2.4 Molecular structure of cellulose (Tsoumis, 1991)

2.2.2 Hemicellulose

Hemicellulose is a polysaccharide, and composed of a number of different sugar units consisting of glucose, mannose, xylose, galactose and arabinose. Unlike cellulose, hemicellulose is of low molecular weight, amorphous and exhibits chain branching. The main backbone of hemicellulose also has short branches of sugar units attached. They also differ from cellulose in that some of the OH content is naturally acetylated, and there are also carboxylate groups associated with the structures. Because of the generally amorphous morphology, hemicellulose is partially soluble in water, contain the greatest proportion of the accessible OH content of the cell wall, react more readily and less thermally stable than cellulose or lignin. Hemicelluloses appear to act as interfacial coupling agents between the highly polar surface of the microfibrils and the much less polar lignin matrix. The hemicelluloses form H-bonds with the surface of the microfibrils and covalent linkages with the lignin matrix. In addition, the constituents of hemicelluloses vary from plant to plant (Hill, 2006).

2.2.3 Lignin

Lignin is a highly amorphous phenolic polymer of indeterminate molecular weight. Lignin, which is generally regarded as an adhesive in the cell wall, is a hydrocarbon polymer consisting of aliphatic and aromatic components. All plant lignins consist mainly of three basic building blocks of guaiacyl, syringyl and *p*-hydroxyphenyl moieties, although other aromatic type units also exist in many different types of plants (Rowell and Han, 2004) as shown in Figure 2.5. Lignin has a disordered structure and is formed through ring opening polymerization of phenyl propane monomers and polymerization to produce a random three-dimensional network via a free radical mechanism. Due to the random nature of the polymerization reaction, there is no definitive structure of lignin, although the frequency of individual bond types is well established. Lignin also provides rigidity, hydrophobic and decay resistance to the cell wall of lignocelluloses fibers. Lignin is responsible for providing stiffness to the cell wall and also serves to bond individual cells together in the middle lamella region (Bledzki *et al.*, 1999; Hill, 2006).

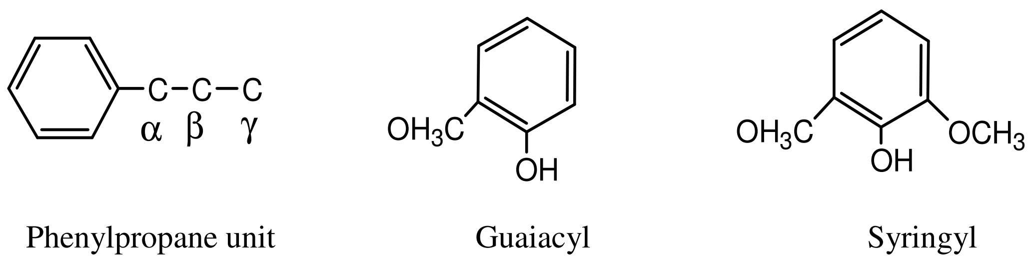

Figure 2.5 Building blocks of lignin (Rowell and Han, 2004)

2.3 Properties of Lignocellulosic Fibers

2.3.1 Physical properties of lignocellulosic fibers

The structure, microfibril angle, cell dimensions, defects, and the chemical composition of fibers are the most important variables that determine the overall properties of the fibers. The dimensions of individual cells of natural fibers depend on the species, maturity and location of the fibers in the plant and also on the fiber extraction conditions. Transversely, unit cells in all of the lignocellulosic fibers have a central hollow cavity called the lumen. The shape (round, polygonal or elliptical) and size of the lumen depends on the source of the fiber and thickness of the cell wall (Reddy and Yang, 2005; Maya and Sabu, 2008). The presence of the hollow lumen decreases the bulk density of the fiber and acts as an acoustic and thermal insulator. These properties make lignocellulosic fibers preferable for lightweight composites used as noise and thermal insulators in automobiles (Reddy and Yang, 2005).

Natural fibers are multicellular and contain a few cylinder cells with various sizes, shapes and with different arrangement. The characteristics of individual fibers depend on the shape, size, orientation and cell walls thickness (Satyanarayana *et al.*, 1990). The scanning electron micrographs obtained confirmed that the cell wall structure of all oil palm fibers consists of a primary layer (P) and secondary layers (S1, S2, and S3). This structural makeup is similar to that of wood cell wall structure as reported by Abdul Khalil *et al.* (2008). Table 2.2 shows morphological properties of oil palm fiber in comparison with hardwood and softwood.

Table 2.2: Morphological properties of oil palm fiber in comparison with hardwood and softwood (Amar *et al.,* 2005)

Properties	OPEFB	OPF	OPT	Hardwood	Softwood
Fiber length (mm)	0.67	1.03	1.37	0.83	2.39
Width of fiber (µm)	12.50	15.10	20.50	14.70	26.80
Width of lumen (µm)	7.90	8.20	17.60	10.70	19.80
Runkel ratio	0.59	0.84	0.26	0.37	0.35
Area of fiber (μm^2)	75.60	126.20	86.70	79.00	256.10

2.3.2 Mechanical properties of lignocellulosic fibers

Fiber strength is an important factor in fiber selection for certain applications. To obtain maximum potential of the lignocellulosic fibers, there are some important physical property requirements to be met for particular utilizations (Rowell and Han, 2004). Table 2.3 gives the data for mechanical and physical properties of lignocellulosic fibers and synthetic fibers. It also shows that mechanical and physical properties of the fibers are different for each fiber based on the fiber types. This information can be a guideline to choose fibers for a particular utilization

Table 2.3 Mechanical and physical properties of lignocellulose fibers and synthetic fibers (Sreekala *et al.,* 1997; Bledzki *et al.,* 1999)

Fibers	**Density**	**Stiffness (GPa)**	**Strength (MPa)**	**Strain (%)**
Glass fibers	2.56	72	3530	4.8
Carbon	1.4	235-827	2200-4410	0.27-1.5
OPEFB	0.7-1.55	2.0	248	14
Flax	1.5	27.6	345-1035	2.7-3.2
Jute	1.3	26.5	393-773	1.5-1.8
Sisal	1.5	9.4-22.0	511-635	2.0-2.5
Banana	1.4	7-20	500-700	1-4
Pineapple	1.44	35-80	400-1600	0.8-1.6
Softwood	1.4	10-50	100-170	-
Hardwood	1.4	10-70	90-180	-

The structure and properties of the fiber are determined by the amount of cellulose and non-cellulosic constituents in a fiber and also influence its crystallinity and moisture regain. Properties such as density, electrical resistivity, tensile strength, modulus, moisture regain and crystallinity is related to the composition and internal structure of the fibers. Generally, fibers with higher cellulose content, higher degree of polymerization of cellulose and lower microfibrillar angle give better mechanical properties. However, the strength of fibers cannot be exactly correlated to the cellulose content and microfibrillar angle. Fibers with higher lignin content, lower l/d ratio and higher microfibrillar angle show lower strength and modulus but have higher extensibility (Reddy and Yang, 2005).

The composition, structure and number of defects in a fiber will influence the mechanical properties of natural fibers. Fibers having higher cellulose content, the cracks propagate through weak bonding between cells, causing intercellular fracture without the removal of microfibrils, whereas cracks propagate through the cells in fibers with lower cellulose content resulting in intracellular fracture with microfibrillar pullout. Elongation of fibers depends on the degree of crystallinity, orientation and the angle of the microfibrils to the fiber axis.

Cellulosic fibers change their dimensions and properties with varying moisture content and the amount of hemicellulose, lignin, crystallinity and surface characteristics of the fibers determined the extent of changes in a fiber. Moisture content in fibers influences the degree of crystallinity, crystallite orientation, tensile strength, swelling behavior and porosity of the fibers. An increase in moisture content decreases the electrical resistivity and affects the dimensional stability of composites made from cellulosic fibers. The ability of a fiber to absorb or desorb moisture should be considered when evaluating the suitability of the fibers for various applications, especially for textiles, paper and composites (Reddy and Yang, 2005).

Abdul Khalil *et al.* (2008) reported that size, shape, and cell wall structure of oil palm fibers generally show high variation. All of these fiber structures are almost round in shape. The S1, S2, and S3 layers are bonded strongly together and form a sandwich-like structure where the microfibril angles of S1 and S3 are parallel with the S2 layer. This sandwich structure gives additional strength to the fiber so that it exhibits collapse resistance against water tension, buckling resistance against axial compressive forces, and bending stiffness toward bending forces. This is because this layered structure will give high hoop strength to the S1 and S3 layers that will prevent the buckling process of the S2 layer when stress is applied at a low level.

In composite technology, these structures will also possess high toughness due to the weak interface element between cell wall layers that is supported by the Gordon-Cook theory. The reinforcement mechanism of certain composites depends on the stress transferred from the matrix substance (resin) to the fiber that is buried inside. According to this theory, the interface area acts as if stopping the cracks in fiber-reinforced composites. This seems to build the toughness of certain composites (Abdul Khalil *et al.,* 2008).

Fibers with uniform circular cross section and a certain aspect ratio normally improve the strength. However, the capability of irregularly shaped fibers with low aspect ratio, as in OPEFB to support stresses transferred from the polymer matrix is significantly reduced. OPEFB fibers have the tendency to exist in bundles. This would mean that the fibers embedded in the matrix would have greater diameters as compared to other wood-based fillers. This in turn would reduce the aspect ratio of the fibers (Amar *et al.,* 2005).

2.3.3 Advantages of lignocellulosic fibers

Due to increasing environmental awareness, the interest in the utilization of natural fibers as a potential alternative for man-made fibers in composite materials has grown among researchers throughout the world. Studies on natural fibers such as OPT and OPEFB (Sreekala *et al*., 2002b) have shown that natural fibers have the potential to be an effective reinforcement in thermoplastics and thermosetting materials. Natural fibers are abundant in nature and are not fully utilized. It was estimated that there was over 30 million tonnes of natural fibers available, especially oil palm fibers (Sreekala *et al*., 2002b).

The growing interest in lignocellulosic fibers is mainly due to their economical production with few requirements for equipment and low specific weight, resulting in a higher specific strength and stiffness when compared to glass reinforced composites. Lignocellulosic fibers also offer several advantages as they are inexpensive, recyclable, abundant, low density, and low strength to weight ratio (Mishra *et al*., 2003; Maya and Sabu, 2008). Furthermore, they exhibit good mechanical properties, provide better working conditions and are less abrasive to equipment compared to common synthetic fibers, which in turn contribute to significant cost reductions (Rozman *et al*., 2001). According to Kuruvilla *et al.* (1995), the lignocellulosic fibers have many advantages such as low cost, low density, high specific strength and modulus, limited requirements on processing equipments, no health problems and availability as renewable natural resources with production requiring little energy.

All these characteristic make their use very attractive to the manufacture of polymer matrix composites (Drzal and Madhukar, 1993). However, natural fibers cannot replace synthetic fibers because natural fiber composites endure from low modulus, low strength, and poor moisture resistance compared to synthetic fiber composites such as glass fiber composites (Abdul Khalil *et al.*, 2007).

The OPEFB and oil palm mesocarp fibers are two important types of fibrous materials left in the palm oil mill. Oil palm fibers are hard and tough, and have potential as reinforcement in phenol-formaldehyde resin (Maya *et al.*, 2004). The renewed interest of lignocellulosic fibers over their synthetic fiber counterpart is that they are abundant in nature and are also renewable raw materials. Owing to their low specific gravity, which is about 1.25–1.50 g/cm^3 as compared to glass fibers, which is about 2.6 g/cm^3, the lignocellulosic fibers are able to provide a high strength-to-weight ratio in plastic materials (Abu Bakar and Abdul Khalil, 2005).

The usage of lignocellulosic fibers also provides a healthy working condition than the glass fibers, since glass fiber dust from the trimming and mounting of glass fiber components causes skin irritation and respiratory diseases among workers. Lignocellulosic fibers are also less abrasive than glass fiber, and offer a friendly processing environment and the wear and tear of tools could be reduced. Furthermore, lignocellulosic fibers offer good thermal and insulating properties, are easily recyclable and biodegradable. These advantages have gained interest in the automotive industry, where materials of light weight, high strength-to-weight ratio, and minimum environmental impact are required. Other than the automotive industry, lignocellulosic fiber composites have also found their application in the building and construction industries, as materials for panels, ceilings and partition boards (Abu Bakar and Abdul Khalil, 2005).