IMPREGNATION OF OIL PALM TRUNK LUMBER (OPTL) USING THERMOSET RESINS FOR STRUCTURAL APPLICATIONS

by

CHE KU ABDULLAH BIN CHE KU ALAM

Thesis submitted in fulfillment of the requirements for the degree of Master of Science

2010

ACKNOWLEDGEMENT

Alhamdulillah, a great thankful to The Great Almighty, Allah for the guidance and blessing until I accomplished my master project and thanks for my beloved family for their support and encouragement.

Firstly, I would like to dedicate my appreciation and pay gratitude to my supervisor, Prof. Dr. Abdul Khalil Shawkataly for his guidance, persistence encouragement and associated aid through this study.

I would also like to express my sincere and affectionate thanks to my co-supervisor Assoc. Prof. Dr. Mahamad Hakimi Ibrahim and all the staff of Bioresource, Paper and Coating Technology Division for their support, contribution and encouragement to me. Thanks to Lim Chin Joo Sawmill Sdn. Bhd for their contribution on lodging, cutting and drying of the oil palm trunk.

A special dedication also goes for En. Abu, En. Raja and En. Farim who had helped me on the technical equipment and preparation of raw materials. Besides, thanks also to all my friends at USM who had share the precious moment together during this year.

I really appreciate all the contribution that have been made and this master project had given me a lot of information and experience that I believe I cannot get it at somewhere else.

Thank you very much.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATES

PF	Phenol formaldehyde
UF	Urea formaldehyde
OPT	Oil palm trunk
OPTL	Impregnated oil palm trunk lumber
RW	Rubberwood
KD	Kiln Drying
MC	Moisture content
SEM	Scanning electron microscopy
TGA	Thermogravimetric analysis
ASTM	American Societies and Testing Materials
BS	British Standard
FRIM	Forest Research Institute Malaysia

GLOSSARY

New Wood Lumber – Composite Lumber

Compreg – Process wood whose cells are impregnated with a resin and compressed, to reduce shringking and swelling and to increase density and strength.

IMPREGNASI KE ATAS PAPAN BATANG KELAPA SAWIT MENGGUNAKAN RESIN TERMOSET UNTUK APLIKASI STRUKTUR.

ABSTRAK

Batang kelapa sawit berusia 25 tahun diambil dan dikeringkan menggunakan kiln bagi mendapat kandungan lembapan yang diperlukan. Sifat-sifat batang kelapa sawit yang diimpreg dengan fenol formaldehid (PF) dan urea formaldehid (UF) dikaji untuk aplikasi struktur. Impregnasi ke atas batang kelapa sawit telah disediakan dengan resin yang berbeza (fenol formaldehid dan urea formaldehid) dalam masa yang berbeza (15 min, 30 min dan 45 min) menghasilkan muatan resin yang berbeza (25%, 50% and 75%). Sifat-sifat fizikal, mekanikal, termal dan kesan pendedahan biologi terhadap kayu batang kelapa sawit yang di impregnasi dibandingkan dengan batang kelapa sawit kering dan kayu getah. Sifat termal dikaji dengan menggunakan analisis termogravimetrik (TGA) dan mikroskopi elektron imbasan (SEM) digunakan untuk mengkaji struktur ultra batang kelapa sawit dan kedudukan resin PF dan UF dalam batang kelapa sawit yang diimpregnasi. Sifat-sifat mekanikal seperti lenturan, tegangan, hentaman dan mampatan daripada batang kelapa sawit yang diimpregnasi menunjukkan kekuatan yang lebih baik berbanding batang kelapa sawit kering. Sifat-sifat fizikal kayu batang kelapa sawit yang diimpregnasi seperti kandungan lembapan, ketumpatan, penyerapan air dan pengembangan ketebalan adalah lebih baik berbanding batang kelapa sawit kering dan juga kayu getah. Kayu getah masih menunjukkan sifat kekuatan yang lebih berbanding kayu kelapa sawit yang diimpregnasi. Bagi sifat kestabilan termal, muatan resin sebanyak 75% dalam kayu kelapa sawit menunjukkan ciri kestabilan termal yang tinggi berbanding muatan resin dalam kayu kelapa sawit yang lain (50% dan 25%), batang kelapa sawit kering dan kayu getah. Pengujian terhadap kesan biologi menunjukkan kayu kelapa sawit yang diimpregnasi mempunyai ketahanan yang tinggi terhadap anai-anai dan pengorek kayu berbanding batang kering kelapa sawit dan kayu getah. SEM menunjukkan bahawa antara impregnasi PF dan UF resin, kadar penetrasi PF resin lebih tinggi dan menghasilkan ikatan fiber-matriks yang lebih baik di dalam batang kelapa sawit

IMPREGNATION OF OIL PALM TRUNK LUMBER (OPTL) USING THERMOSET RESINS FOR STRUCTURAL APPLICATIONS

ABSTRACT

The 25 years old oil palm trunks were taken and kiln dried to achieve required moisture content. The properties of kiln dried oil palm trunk (OPT) impregnated with phenol formaldehyde (PF) and urea formaldehyde (UF) was studied for structural application. Impregnation technique of OPT with resins (PF and UF) were prepared at different times (15 min, 30 min and 45 min) and different resin loadings (25%, 50% and 75%). The physical, mechanical, thermal and biological properties of impregnated oil palm trunk lumber (OPTL) were studied and compared with dried OPT and rubberwood. The thermal properties were determined through thermogravimetric analysis (TGA) and scanning electron microscopy (SEM) was used to observe the ultra structure and location of PF and UF resin in OPTL. In general, the flexural, tensile, impact and compression properties of OPTL were higher than dried OPT (control). The moisture content, density, water absorption and thickness swelling of OPTL were lower as compared to dried OPT and rubberwood. OPTL with PF resin showed higher physical, mechanical, thermal and biological properties as compared to OPTL with UF resin. Rubberwood properties still exhibited the highest mechanical properties than OPTL. Thermal properties of the OPTL with 75% resin loading showed higher thermal stability as compared to other different resin loadings of OPTL (25% and 50%), dried OPT and rubberwood. The biological exposure on both OPTL with PF and UF resin showed high resistance against termite and wood borer. As SEM showed with comparison between PF and UF impregnation, PF resin loading in the OPTL proved higher penetration as it was more embedded with more complete fiber-matrix bonding.

CHAPTER 1: INTRODUCTION

1.1 General

The oil palm tree (*Elaeis guineensis*) which was introduced in 1917 is one of the most important commercial crops in Malaysia and has brought in enormous sum of foreign exchange in export earnings which accounted for 4% of the nation's total export of merchandise in the year 2000 with a market share of about 50 to 58%, respectively (Nasir, 2003). The oil palm is generally planted for oil-producing fruit to make cooking oil. Since so many waste from oil palm tree, the botanical and cultivation aspect of the oil palm have been extensively studied. (Hartley, 1977; Corley and Gray., 1976).

Oil palm generally has an economical life span of about 25 years and oil palm tree would be replanted after 25 to 30 years old and this process would contribute to a high amount of agricultural waste in our country. During the replanting process, the waste would be generated in the form of felled trunk and fronds. As the world's leading exporter of oil palm, Malaysia had at least 4 million of oil palm plantation. It has been estimated that about 13.2 million tonnes of waste will be available during replanting (Kamarulzaman *et al.*, 2004).

In wood based industry, the shortage of wood as a raw material has become eminent recently. This is due to many plant producing wood based products especially plywood and lumber had closed down. However, recently the wood based industry is facing problem with the supply of raw materials not only from the natural forest, but rubber plantation as well. Yearly it was estimated at least 20 million of solid wood used in wood based industry.

Therefore, it is very important to find alternative source for local raw material and oil palm biomass appear to be the most viable alternative especially oil palm trunk which is possible to be utilized as value added product as well as future wood-based industry (Mohamad *et al.*, 2005). The advantages of oil palm trunk is in forms of optimized performance, minimized weight and volume, cost effectiveness, fatigue and chemical resistance controlled bio degradability and environmental considerations. "New wood-lumber" is form by combining oil palm trunk with other material present many opportunities.

Waste from agriculture materials are being combined with other lignocellulosic material, metals, plastics, glass and synthetic fibers, and the properties of these composites are still studied (Hill *et al.*, 1998). A fundamental research demonstrated that oil palm trunk could be engineered into a palm 'wood' or solid oil palm trunk; however the results did not promising. Kiln dry methods showed a high degree of shrinkage, checks, warping, twisting and collapse with low recovery, expensive cost processing and difficult to dry (Anis *et al.*, 2005).

Whereas, new oil palm trunk exhibit superior and good permeability through modification with microwave technique 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, low toxicity and odorless, good polymerization completion, less heat generation at polymerization, and low price (Drzal and Madhukar, 1993).

Many studies on the oil palm trunk showed the potential of utilizing this agricultural waste for several types of value added products such as high performance panel products, pulp and papermaking, and animal feed (Sreekala *et al.*, 2002; Abdul Khalil *et al.*, 2001; Henson, 1999). In addition, a number of studies were made to improve the properties of oil palm trunk such as dimensional stability, durability and strength (Edi Suhaimi et al., 2008; Erwinsyah, 2008; Bakar, 1999). Meanwhile, the modification of wood with phenolic resin has been done by Furono *et al.* (2004) to enhance the dimensional stability and biological exposure. Moreover, the treatment of wood by "compreg" method using low molecular weight of phenol formaldehyde has been studied to gain better wood characteristics (Shams *et al.*, 2004). In this study, the oil palm trunk lumbers were impregnated with two types of resin which is phenol formaldehyde (PF) and urea formaldehyde (UF).

The impregnated oil palm trunk (OPTL) acts as reinforcement in the polymer matrix which improves the strength, stiffness, hardness, wear proof properties, mechanical, physical, dimensional stability, chemical proof properties, decay and surface beauty compared to ordinary wooden lumber (Torgovnikov and Vinden , 2000). This study expected, impregnation process obtained fully resin penetrated into oil palm trunk structures, gain better strength and resistance to environmental exposure. In the mean time, thermoset resin improved the thermal stability of the oil palm trunk lumber (OPTL). There are a wide range of applications in industry, transportation, home and recreation. Specific product areas include wall panels, sub floors, roof panels, doors, furniture parts and specialized containers.

1.2 Objectives

1. To produce the oil palm trunk lumber (OPTL) using impregnation technique at different time (15 min, 30 min and 45 min).
2. To study the effects on physical, mechanical, thermal properties and biodeterioration exposure of using different resin loading (25, 50 and 75%) with different types of resin (PF and UF) to the oil palm trunk.
3. To study the physical, mechanical, thermal properties and biodeterioration exposure of impregnated oil palm trunk lumber and comparison with dried OPT and rubberwood (RW).

1.3 Justification

The raw material used in this study was oil palm trunk (OPT). It has been chosen on account of being a waste material and abundantly available in Malaysia. To date, no studies have been undertaken in this area and its commercial value has not been fully discovered. Most of oil palm trunk has been utilized on plywood industries, animal feed and alcohol production. Literature review survey revealed that only impregnation of oil palm trunk with low molecular weight phenol formaldehyde resin has been studied. Therefore, this study focused on use of two types of commercial resins for impregnation into oil palm trunk which were phenol formaldehyde and urea formaldehyde. In addition, the resin loading was a parameter to determine the properties of oil palm trunk lumber and compare with rubberwood.

CHAPTER 2: LITERATURE REVIEW

2.1 The Oil palm

2.1.1 Introduction

The oil palm is a tropical palm tree; therefore it can be cultivated easily in Malaysia. The oil palm tree cultivated in Malaysia is originated from West Africa where it was growing wild and later developed into an agricultural crop. The first commercial oil palm estate in Malaysia was set up in 1917 at Tennamaran Estate, Selangor (Sumathi *et al.*, 2008). Today, the oil palm planted area in Malaysia is over 4 million ha (MPOB, 2007) and with this large hectare of oil palm plantation, the number of oil palm trunks (OPT) available (as a result of replanting activities) at any time is enormous (Abdul Hamid *et al.*, 2008). It has been estimated that felling in Malaysia alone yields approximately 85 tons of stem per hectare (Haslett, 1990).

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 numbers of biomass wastes. The amount of biomass produced by an oil palm tree, include of the oil and lignocellulosic materials is on the average of 231.5 kg dry weight/year. In the year 2008, oil palm empty fruit bunches and oil palm trunk is contributor of oil palm biomass, whereby about 15.8 and 8.2 million tonne, respectively have been produced annually.

Oil palms are usually felled after the age of 25 years, either due to their decreasing yield or because they have grown too tall which makes harvesting very difficult. For the disposal of oil palm stems, they are normally left to rot or are burnt in the field. However, freshly felled stems with their high moisture content cannot be easily burnt in the field. Leaving the stems in the field without further processing will physically hinder the process of planting new crops as the stem can take about five years to decompose completely. Meanwhile, they serve as the breeding grounds for insect pests such as rhinoceros beetles *(Oryetes rhinoceros)* and stem rotting fungi *Ganoderma* spp. The practice of disposing oil palm stems by burning is now considered unacceptable as it creates air pollution and affects the environment (Lim & Gan, 2005). The oil palm tree and replanting process of oil palm at plantation area are shown in Figures 2.1 and 2.2.

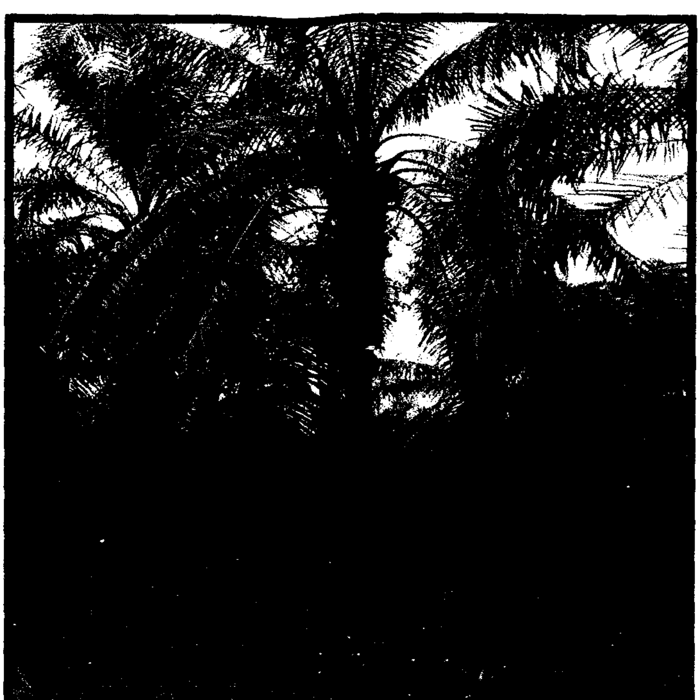


Figure 2.1: 25 years old oil palm tree.

Figure 2.2: Replanting process (Erwinsyah, 2008).

Agro-wastes from the oil palm industry such as oil palm trunks (OPT), oil palm fronds (OPF) and empty fruit bunches (EFB) have attracted attention as potential sources for new value added materials. The chemical, physical and mechanical properties of the oil palm biomass indicate that these materials are similar to wood, and they may be suitable raw materials for wood based panels (Abdul Khalil *et al.*, 2008).

Palm oil biomass can be utilized to produce various types of value added products. The oil palm biomass such as the EFB and OPF have been modified and processed to produce molded oil palm (MOP) products. MOP products are unique bio-based materials made from oil palm particles and thermoset resin in matched metal disc under heat and pressure. MOP products are extremely versatile and can be used in furniture, building, electronics, packaging and automobile industries (Sumathi *et al.*, 2008).

Composites such as plywood, blockboard and fibreboard can be produced from parts of oil palm trunk. Besides, trunks, fronds, and EFB can be used as material for one- and three-layer particleboard, bonded with resin. The denser material from the base of the trunk can be used to make furniture after treated with suitable resin. Several of these uses have been tested successful for usable materials have been produced (Koh *et al.*, 1999). Recently, lignocellulosic wastes such as oil palm fibres, rice straw and banana stem have been used as fillers in composite materials for diverse applications such as automotive parts, flooring, doors, fence panels and outdoor structures (Abdul Khalil *et al.*, 2008).

2.2 Oil Palm trunk

2.2.1 General

It has been estimated that felling in Malaysia alone yields approximately 85 tons of stem per hectare (Haslett, 1990). The expected large volume of oil palm stem available annually due to replanting, the task of finding ways to utilise this enormous amount of lignocellulosic material is great (Lim & Gan, 2005). Most of the oil palm trunk is converted into various types of wood such as saw-wood and ply-wood or lumber. With the decreasing supply of raw materials from traditional sources such as rubber wood and tropical hardwoods, utilizing of oil palm trunk (OPT) as an alternative lignocellulosic raw material for wood based industry is very crucial. The shortage of raw material will lead to a difficult situation to maintain the current production level in wood based industry.

Considering to the physical and mechanical properties of OPT, one is dealing with a material with a material that 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 oil palm trunk (OPT) as compared to solid sawn OPT timber for conversion into various products (Hashim *et al.*, 2006).

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

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

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 have high moisture content and enormous variation in density.

iv. The trunk becomes spongy near to the core due to the anatomical characteristics.
v. The trunk is inconsistent in the physical characteristics.
vi. The cutting knife easily blunt due to the presence of the silica.
vii. The trunk veneer absorbed more adhesives as compared to tropical hardwoods because of the rough surfaces.

Oil palm lumber has been successfully utilized as core in the production of blackboard. The saw-wood produced from oil palm can be used to make furniture but not for building structure due to its low specific density. However, the strength of the ply-wood produced from oil palm was found to be comparable with commercial ply-wood. Oil palm trunk also has been used to produce particleboards with chemical binders. Moreover, some of the trunks are mixed with EFB and oil palm fibers to be combusted and produce energy (Sumathi *et al*, 2008).

2.3 Properties of oil palm trunk

2.3.1 Anatomy of oil palm trunk

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 *et al.,* 2007). Oil palm trunk has no cambium, secondary growth, growth rings, ray cells, sapwood and heartwood or branches and knots in the oil palm trunk. The growth and increase in diameter of the trunk is resulted from the overall cell division and cell enlargement of the vascular bundles fibers. Looking at a cross sectional view of the oil palm trunk, its distinguished three main parts; cortex, peripheral region and central. It also contains vascular bundles and parenchymatous tissue zone (Killmann and Lim, 1985).

2.3.1.1 Cortex, periphery and central

A narrow cortex, which is approximately 1.5 to 3.5 cm wide, makes up the outer part of the trunk. Figure 2.3 illustrated the main part of oil palm trunk which consist cortex, peripheral and central region. It is largely composed of ground parenchyma with numerous longitudinal fibrous strands of small and irregular shaped fibrous strands and vascular bundles.This region with narrow layers of parenchyma and congested vascular bundles, give ride to a sclerotic zone which provides the main mechanical support for the palm stem. The central zone, which makes up about 80% of the total volume of oil palm trunk is composed of slightly larger and widely scattered vascular bundles embedded in the thin wall parenchymatous ground tissues. Towards the core of the trunk the bundles increase in size and are more widely scattered.

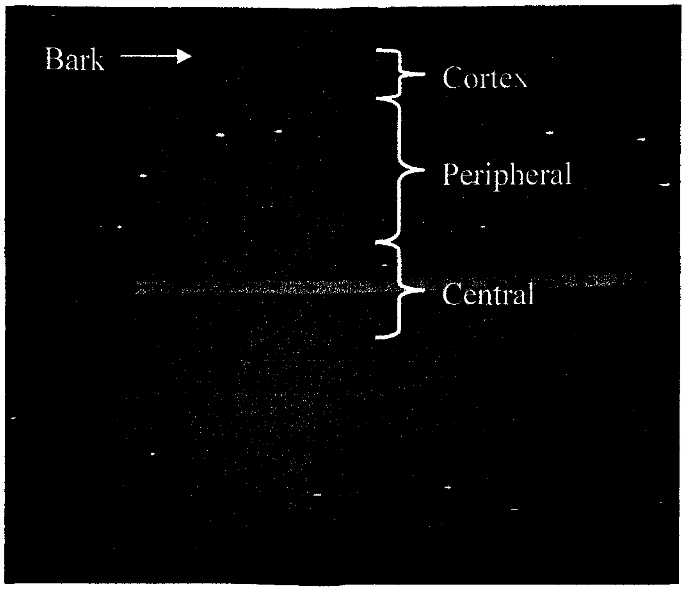


Figure 2.3: Oil palm trunk crosscut section.

2.3.1.2 Vascular bundles

Each vascular bundle is basically made up of a fibrous sheath, phloem, xylem and parenchyma cells. The number of vascular bundles per unit area decrease towards the inner zones and increase from the butt end to the top of the palm (Lim and Khoo, 1986). The xylem is sheathed by parenchyma and contains mainly one or two wide vessels in the peripheral region and two or three vessels of similar width in the central and core region. Though rare, bundles with more than three vessels arranged tangentially or in clusters can also be found scattered, particularly in the core region. Extended protoxylem, reduced vascular tissue and small bundles with little fibrous tissue are also commonly found scattered among the wider bundles in the core region. The distribution of fibrous strands depends on the number of bundles present (Lim and Khoo, 1986). The peripheral region normally contains a large number of radially extended fibrous sheathed, thus providing the mechanical strength to the palm.

The fibers have multi-layered secondary walls and increase in length from the periphery to the pith. The basal part of the stem, being older, normally has better developed secondary walls than do the top parts. The phloem cells, in single strand, are present between the xylem and fibre strands. In the peripheral sclerotic region, the bundles are generally smaller and in some cases, almost disappear. The area occupied by the phloem, which is in the form of an inverted triangle, increases in size as the bundles become larger in the central region.

2.3.1.3 Parenchymatous tissue

The ground parenchymatous cells (Figure. 2.4) consist mainly of thin-walled spherical cells, except in the area around the vascular bundles. The walls are progressively thicker and darker from the inner to the outer region.

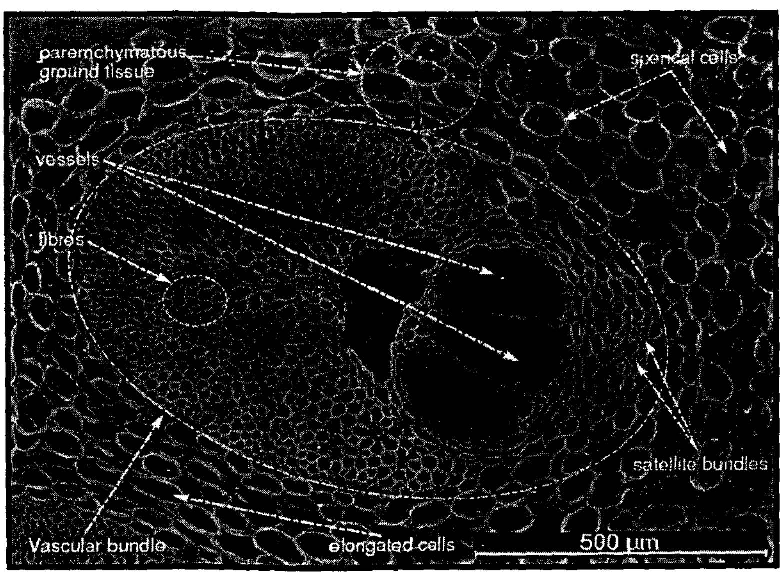


Figure 2.4: Structure of vascular bundle of oil palm wood at transverse section detail with the existence of parenchymatous ground tissue, vessels, fibers and phloem (Erwinsyah, 2008).

2.3.2 Chemical composition of oil palm trunk

The variation in chemical composition across the trunk at the 1.8 m height level in one tree was difficult to generalize (Yusoff *et al.,* 1984). However, Abdul Khalil *et al.* (2008) have characterized the chemical composition of oil palm trunk which is shown in Table 2.1.

Table 2.1: Chemical composition of oil palm trunk (Abdul Khalil *et al.*, 2008)

Composition	Extractive (%)	Hemicellulose (%)	Cellulose (%)	Lignin (%)	Ash (%)
Oil palm trunk (OPT)	5.35	73.06	41.02	24.51	2.2

Respectively, the lignocellulosic contents of oil palm trunk is markedly lower but shows higher content of extractives, as well as water and alkali soluble than coconut wood and rubberwood (Husin *et al.*, 1985). In a separate study, observed that the lignin content was fairly evenly distributed throughout the tree except that the core in the upper region was slightly deficient in the component whilst the bottom contained an excessive amount (Halimahton and Ahmad, 1990).

The lignin content range varies between 15% and 21.7%. The results are consistent with the fact that the number of fibrous vascular bundles increases towards the peripheral region and thickening of the older vascular bundles gives rise to the higher lignin content of the lower trunk. The ash content also observed to be similar throughout the trunk with the range varies between 3.0% and 3.3%. Table 2.2 showed the various chemical compositions of oil palm trunk, coconut trunk and rubber wood trunk.

Table 2.2: Various chemical composition of oil palm trunk, coconut trunk and rubberwood (Corley, 1976).

Chemical composition	Oil palm trunk	Coconut trunk	Rubberwood
Holo-cellulose	45.7	66.7	67
Alpha-cellulose	29.2	-	41.5
Acid cellulose lignin	18.8	25.1	26
Pentosans	18.8	22.9	19.4
Ash	2.3	2.8	1.5

Freshly felled oil palm trunk may yield up to 10% free sugars and 25% starch (Sudin *et al.*, 1987). In advance, total content of free sugars of 2 to 10% throughout the trunk height. The core regions were found to elaborate higher proportion of free sugars as shown by the methanol-water extracts whilst the peripheral zones had the lowest. According to analysis by high performance liquid chromatography (HPLC) revealed sucrose, glucose and fructose as the three main free sugars of the oil palm trunk.

Further the authors indicated that analysis free sugar by acid hydrolysis of oil palm trunk produced higher amount of sugars, ranging between 48% and 70%. Examination of the HPLC trace of the acid hydrolyzate showed the presence of six sugar components namely glucose, xylose, galactose, arabinose, mannose, and rhamnose, with glucose being the major component (35 to 48%) followed by xylose (11 to 16%). (Halimahton and Ahmad, 1990).

2.3.2.1 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 2.5. This results in the cellulose backbone being linear and cellubiose units link together via glicosidic 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 which produces a strong crystalline structure and as reinforce element in the cell wall.

The microfibrils have associated with 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 structure. 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 conditions, 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.

2.3.2.1 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 2.5. This results in the cellulose backbone being linear and cellubiose units link together via glicosidic 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 which produces a strong crystalline structure and as reinforce element in the cell wall.

The microfibrils have associated with 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 structure. 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 conditions, 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.

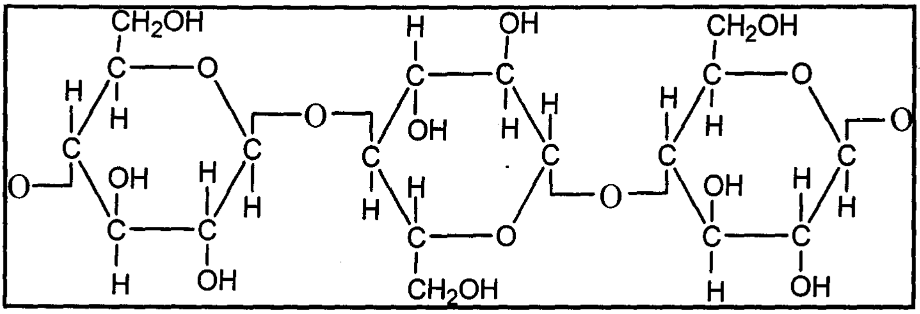


Figure 2.5: Molecular structure of cellulose (Tsoumis, 1991)

2.3.2.2 Hemicellulose

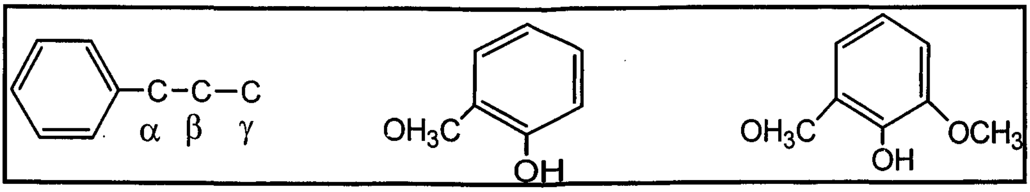
Hemicellulose is polysaccharides and they are composed of a number of different sugar units consisting of glucose, mannose, xylose, galactose and arabinose. Unlike cellulose, hemicellulose is of low molecular weight, amorphous and exhibits chain branching. The main backbone of hemicellulose also has 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.

As 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. Besides that, the constituents of hemicelluloses vary from plant to plant (Hill, 2006).

2.3.2.3 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 (Bledzki *et al.*, 1999). The molecular structure of lignin is shown in Figure 2.6. 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 to lignin, although the frequency of individual bond types is well established. Lignin also provides rigidity, hydrophobicity 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 (Hill, 2006).



Phenylpropane unit Guaiacyl Syringyl

Figure 2.6: Building blocks of lignin (Rowell and Han, 2004)

2.3.2.4 Pectin and waxes

Pectin is a polysaccharide consisting polygalacturon acid. Maya and Sabu (2008) cited that pectin is the major matrix component within the cell wall of lignocellulose fibers especially in non-wood fibers. Pectins are a collective name for heteropolysaccarides and they give plants flexibility. Waxes make up the last part of fibers and they consist of different types of alcohols (Maya and Sabu, 2008). Waxes also consist of different type of alcohols which are insoluble in water and also in certain acids such as palmitic acid, oleaginous acid and stearic acid. They can only be extracted from the fibers by using organic solvents.

2.3.3 Physical properties of oil palm trunk

Physical properties of oil palm trunk are important in contributing its characteristics as a raw material of producing a product which required the properties to stand against load. The main physical properties are moisture content, density and fiber dimension.

2.3.3.1 Moisture content

The initial moisture content of the oil palm wood varies between 100 and 500% and a gradual increase in moisture content is indicated along the trunk height and towards the central region, with the outer and lower zone having far lower values than the other two zones (Lim and Khoo, 1986). An increase in the number of vascular bundles causes the decrease in percentage of parenchyma cells which have high capacity in water absorption (Prayitno, 1995).

Based on the trunk height factor; there was a tendency that the moisture content was decreased from the bottom to the top of the oil palm tree (Bakar *et al.*, 1998). They predicted that it was influence by the effect of earth gravity, where the water distribution to the higher part of the trunk requires higher caviller pressure.

2.3.3.2 Density

Due to its monocotyledonous nature, there is a great variation of density values at different parts of the oil palm stem. Density values range from 200 to 600 kg/m^3 with an average density is 370 kg/m^3. The density of oil palm trunk decreases linearly with the trunk height and towards the centre of the trunk (Lim and Khoo, 1986). This is reflected in the clear distinction observed in hardness and weight between the outer and inner portions and the butt and higher regions of the trunk. The outer region throughout the trunk shows density values over twice those of the inner regions.

These variations are due to several factors. Across the trunk the density is influenced largely by the number of vascular bundles per square unit which decreases towards the centre. However, variations in density along trunk height are due to the vascular bundles being younger at the top and of the palm. Although higher in number per square centimetre, the bundle here are smaller in size and the cell walls are thinner. Figure 2.7 shows the schematic diagram of a density variation in oil palm trunk.

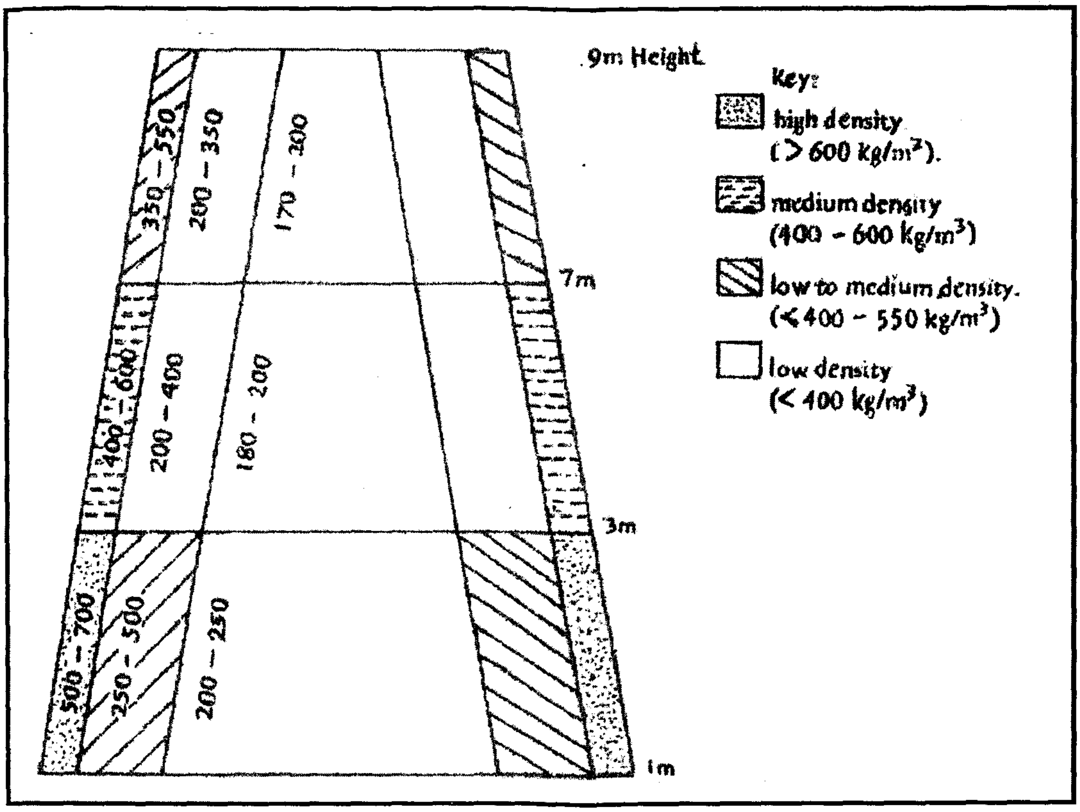


Figure 2.7: Schematic diagram of density variation in oil palm stem (Lim & Khoo, 1986).

Higher density values in the peripheral zone are also due to the following reasons:

a) The presence of radially extended fibrous sheaths.

b) Lesser number of vessels and general absence of extended protoxylem in the outer vascular bundles.

c) Thicker walls of the ground parenchyma cells from the inner to the outer zones.

d) Presence of better developed secondary walls in the fibers.

2.3.3.3 Fiber dimension

The structure, microfibrillar angle, cell dimensions, defects, and the chemical composition of fibers are the most important variables that determine the overall properties of the fibers (Maya and Sabu, 2008). The dimensions of individual cells or 'ultimates' in natural fibers are depends on the species, maturity and location of the fibers in the plant and also on the fiber extraction conditions. Transversally, 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.

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 contain a few cylinder cells with various sizes, shapes and different arrangement. The characteristics of individual fibers are depending on the shape, size, orientation and cell walls thickness (Satyanarayana *et al.*, 1990).

The electron micrographs obtained confirmed that the cell wall structure of all oil palm fibers consists of a primer layer (P) and secondary layers (S1, S2, and S3). This structural makeup is similar to that of the wood cell wall structure reported by Abdul Khalil *et al.,* (2008). Oil palm wood fibers show a slight increase in length from the butt end to a height of 3 to 5 meters before decreasing continuously towards the top.

Longer fibers at the butt are probably due to more matured fibrous tissue in this region. Oil palm fibre length increases from periphery to the inner part. Mean fibre length range from 1.76 mm at periphery to 2:37 mm at the inner part. This is due to the nature of the palm growth where the overall increase in trunk diameter is due to enlargement of the fibrous bundle sheath, particularly those accompanying the vascular bundles in the central region (Killmann and Choon, 1991).

Fibre diameter decreases along the trunk height because broader fibers are to be found in the larger vascular bundles nearer the base of the palm trunk and vice versa (Lim and Khoo, 1986). The fibre dimensions of oil palm trunk compared to those of angiosperms, represented by rubberwood (*Hevea brasiliensis*), and gymnosperms, represented by Douglas fir (*Pseudotsuga menziesii*) are shown in Table 2.3. Oil palm fibers are comparable in length to fibers from rubberwood, but are much shorter than those of Douglas fir.

Table 2.3: Oil palm fiber dimension compared to Douglas fir and rubberwood (Shaari *et al.*, 1991)

Dimension	Oil palm fiber	Rubberwood	Douglas Fir
Length (mm)	1.22	1.4	3.4
Width (μm)	35.2	31.3	40
Thickness of cell wall (μm)	4.5	5	-

2.3.4 Mechanical properties of oil palm trunk

Mechanical properties of oil palm trunk reflect the density variation observed in the trunk both in radial as well as in the vertical direction. Bending strength values are obtained from the peripheral lower portion of the trunk and the central core of the top portion of the trunk gives the lowest strength. Bending strength of oil palm trunk is very low compared with conventional timber species. Variation of the compression strength parallel to grain also follows the same trend as the bending strength. The compression strength value is comparable to rubberwood at similar density value. The hardness value of oil palm trunk is lower than rubberwood as well as coconut wood (Killmann and Lim, 1985).

The average MOE values at various positions shown that those values are indicated a gradual decrease in MOE along the trunk height and depth. The MOE value range varies between 2908 kg/cm^2 and 36289 kg/cm^2. Variation of the MOR also follows the same trend as the MOE. The mean values of MOR at peripheral, central and inner zones were about 295.41 kg/cm^2, 129.04 kg/cm^2 and 66.91 kg/cm^2 , respectively.

Statistical analysis of MOE value showed that the differences in trunk depth effect significantly at the level of 0.01 and the trunk height only influence significantly at the level of 0.05. It means that in order to produce the homogenous lumber, the trunk depth position should be taken into attention, especially in determining the sawing pattern before lumbering process (Bakar *et. al.*, 1999).