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LIST OF ABBREVIATIONS

Abbreviation	Definition
ANOVA	Analysis of variance
ASTM	American Societies and Testing Materials
BS	British Standard
CCD	Central composite design
DOE	Design of experiments
KD	Kiln Drying
MC	Moisture content
OPT	Oil palm trunk
OPTCL	Oil palm trunk core lumber
PF	Phenol formaldehyde
RSM	Response surface methodology
RW	Rubberwood
SEM	Scanning electron microscopy
TGA	Thermogravimetric analysis

LIST OF SYMBOLS

Symbol	Definition	Unit
A	Water absorption	%
D	Density	g/cm^3
m	Mass of the sample	g
M_1	Weight before water absorption	g
M_2	Weight before water absorption	g
MC	Moisture content	% wt.
v	Volume of the sample	cm^3
W_1	Weight of sample before drying	g
W_2	Weight of sample after drying	g

PEMBANGUNAN DAN SIFAT-SIFAT TERAS BATANG KELAPA SAWIT KERING KETUHAR GELOMBANG MIKRO DILMPREGNASI RESIN

ABSTRAK

Dalam penyelidikan ini, pengeringan teras batang kelapa sawit menggunakan gelombang mikro secara optimum telah dilaporkan. Pengoptimuman kaedah pengeringan menggunakan gelombang mikro dapat mengelakkan sampel terbakar dan mengecut di samping meningkatkan kadar ketelapan OPT bagi membangunkan produk baru yang bernilai. Suatu rangka eksperimen telah dicipta oleh pusat ciptaan komposit menggunakan kaedah tindakbalas permukaan untuk diterjemahkan penemuannya secara statistik. Tiga proses bebas menggunakan masa (2, 4, 6, 8, 10 min), berat sampel (300, 475, 650, 825, 100g) dan kuasa (660, 1320, 1980, 2640, 3300 W) telah diuji dibawah kaedah yang telah dicipta oleh program perisian "Design Expert". Keputusan telah menunjukkan bahawa pengeringan menggunakan gelombang mikro telah meningkatkan kecekapan pengeringan dengan pengurangan masa pengeringan dan pembebasan kandungan lembapan lebih baik berbanding menggunakan pengeringan oven yang tidak mempunyai perubahan yang signifikan. Dengan mengaplikasikan keadaan pada 6.89 min disamping kuasa gelombang mikro disetkan pada 4 untuk sampel 1000g, dianggarkan terdapat 14.63% kandunngan lembapan. Teras batang kelapa sawit yang telah dikeringkan menggunakan gelombang mikro telah diimpregnasikan dengan resin fenol formaldehid sebagai matrik melalui vakum tangki impregnasi yang bertekanan tinggi. Teras papan batang kelapa sawit telah diimprenasi dengan perbezaan masa dan dibandingkan dengan kayu getah. Sifat-sifat fizikal, mekanikal dan termal diuji berdasarkan garis panduan BS dan ASTM. Teras papan batang kelapa sawit yang telah dikeringkan melalui gelombang mikro dan diimpregnasi dengan resin menunjukkan sifat fizikal dan

mekanikal yang lebih baik daripada yang dikeringkan sahaja. Manakala sifat bagi teras papan batang kelapa sawit yang telah diimpregnasi selama 60 minit menunjukkan kekuatan yang lebih rendah berbanding kayu getah kecuali sifat serapan air dan termal yang lebih menunjukkan persamaan sifat mahupun lebih baik dari kayu getah. Sifat morfologi teras papan batang kelapa sawit yang telah diimpregnai penuh dengan resin dapat diperhatikan menggunakan SEM dan menunjukkan resin memenuhi ruang sel yang terdapat dalam teras papan batang kelapa sawit.

DEVELOPMENT AND PROPERTIES OF RESIN IMPREGNATED MICROWAVE DRIED OIL PALM TRUNK CORE LUMBER

ABSTRACT

In this study the optimization of drying oil palm trunk core lumber (OPTCL) biomass using microwave radiation was reported. Optimizing of the drying conditions using microwave could avoid burning, shrinkage and increasing the permeability of OPT was aimed to develop a new value added material. Drying the core part of oil palm trunk using microwave was completed in this study for the first time. A set of experiments was designed by central composite design using response surface methodology (RSM) to statistically evaluate the findings and developed a model to predict drying prameters. Three independent process variables including time (2, 4, 6, 8, 10 min), sample weight (300, 475, 650, 825, 1000 g) and input power (660, 1320, 1980, 2640, 3300 W) were studied under the given conditions designed by Design Expert software. The results showed the effectiveness of microwave drying in reducing the time and better removal of moisture as compared to that of oven drying with no significant changes. Employing optimum conditions at 6.89 min of time with a microwave power set at 4 for a sample of 1000 g, predicting 14.28% of moisture content. The microwave dried oil palm trunk core part was impregnated with phenol formaldehyde (PF) resin as a matrix using high-pressure vacuum impregnation chamber. Oil palm trunk core lumber (OPTCL) was impregnated in different times and compared with Rubberwood (RW). The mechanical, physical, and thermal properties were studied according to BS and ASTM standards. On average, the microwave dried impregnated oil palm trunk core lumber (OPTCL) exhibited higher physical and mechanical properties than dried one. The properties of OPTCL impregnated for 60 min was slightly lower than RW except in water absorption and thermal stability which was comparable and even higher than RW.

The morphology of resin loaded oil palm trunk core which was analyzed by scanning electron microscopy (SEM) showed full penetration of resin into OPTCL cell.

CHAPTER 1

INTRODUCTION

1.1. Oil Palm Trunk in Malaysia

The first commercial oil palm estate in Malaysia was set up in 1917. Today oil palm tree (*Elaeis guineensis*) has become one of the most important commercial crops in Malaysia which has brought in enormous sum of foreign exchange in export earnings. The oil-producing fruit of oil palm tree for cooking oil is the main reason that this tree has been planted since the early twentieth century. Malaysia as the world's second producer of palm oil with 4.48 million hectares (Singh *et al.*, 2010) of the crop produces 15.9 million tonnes oil (Mokhtar *et al.*, 2008).

Generally, oil palm tree has an economical life span of about 25 years and would be replanted after 25 to 30 years. This replanting process contributes to a high amount of agricultural waste. It is estimated that more than 70,000 hectar have to be replanted every year, requiring the felling of about 9 million palms (Mokhtar *et al.*, 2008). Figure 1.1 shows the cultivated area for oil palm in Malaysia (divided into three categories, i.e. Peninsular Malaysia, Sabah and Sarawak) within the next four decades. The total land fertilized for oil palm plantation shows considerable rise until 2010. Currently Malaysia is the world's second top producer of palm oil (after Indonesia). After a sharp increase in the production of palm oil from October 2007 to December 2008 the oil palm planted area had increased drastically and contributed about RM 65.19 billion to the Malaysian export. This energy crop provides direct and indirect employment to 860,000 people excluding other multi- plying effects and spin-offs activities. This amount of palm oil production also leads to an enourmeous amount of waste such as OPTCL which needs serious thought (Abdullah *et al.*, 2009).

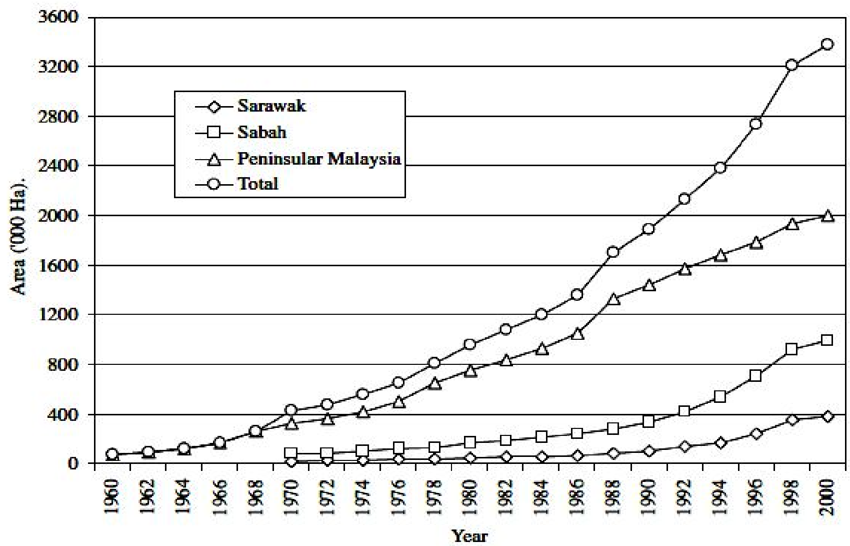

Figure 1.1 Cultivated area for oil palm in Malaysia in the past decades (Butler, 2005)

1.2. Oil Palm Tree

Oil palm tree is a monocotyledons species, which does not have cambium, secondary growth, growth rings, ray cells, sapwood, heartwood, branches and knots. The growth and increase in diameter of the trunk result from the overall cell division and cell enlargement in the parenchymatous ground tissues, together with the enlargement of the fibres of the vascular bundles (Choon *et al.*, 1991). The vascular bundles increase from the butt end to the top of the palm (Choon and Khoo, 1986) and with regards to physical properties, there is variation in the density values at different parts of the trunk. The density values decrease from the outer to the center parts, but it is not clearly related to the trunk height and density values along the trunk (Bakar ES *et al.*, 1999; Bakar *et al.*, 1999). A gradual increase in MC is indicated along the trunk height from the butt end to the top and the density decreases linearly with trunk height and toward the center of the trunk (Killmann and Choon, 1985). The mentioned physical conditions influences the strength properties of the trunk. Bending strength, compression strength parallel to grain and hardness of the trunk is generally poor compare to other timber species including Rubberwood and coconut wood (Choon *et al*., 1991). In fact the mechanical properties of oil palm trunk were approximately two times lower than those of teak and Rubberwood (Ratanawilai *et al.*, 2006).

Preliminary research by the Malaysia Palm Oil Board (MPOB) demonstrated that the oil palm trunk could be engineered into a palm ‘‘wood’’ or solid oil palm trunk. As long as conventional drying methods used in their study caused drying defects such as high degree of shrinkage, checks, warping, twisting, and collapse with low recovery, and the processing cost was too expensive,their results were not promising so far (Abdul Khalil *et al*., 2009).

1.3. Drying Process

Drying of timber is an approach for adding value to sawn products from primary wood processing industries. If drying process is carried out immediately after the felling of trees, the timber can be protected against primary decay, fungal stain and attack by certain kinds of insects. Organisms, which can cause decay and stain, generally cannot thrive in timber with moisture content below 20%. The drying of wood concerns many researchers and timber companies around the world(Kueon, 2008; Vermaas and H.F, 1995). Nowadays, scientists focus on faster, cheaper and more effective drying methods. In traditional methods, it takes weeks and months for air drying, kiln drying and ovens, while with microwave it takes few minutes for the wood samples to reach the desired moisture content (Kueon, 2008). During the past 50 years, research has been conducted to investigate microwave drying of solid wood products but for microwave drying of oil palm trunk (OPT), no study has been reported so far.

1.4. Microwave Drying

Lower temperature drying methods such as air drying and microwave drying results in less damage in structure and dimension of wood (Wang *et al*., 2007). Microwaves are used in laboratories worldwide for drying, calcinations, binder removal, glass melting and sintering of ceramics and powdered metals. Microwave drying of materials is an industrial reality; an advantage of microwave heating is that the entire part couples in the energy field, directly absorbing energy throughout the volume. In microwave firing, heating rates from 100 to 150 °C/min (180 to 270 °F/min) can be used to fully sinter ceramics without cracking. Cooling also is fast because the refractories do not become as hot as in conventional firing. This translates to significant savings in time.

Manufacturers are moving toward microwave technology as the need for standardized microwave furnaces, and the need for inexpensive feasibility studies and experienced help with microwave scale-up has been overcome. Several companies are rising to the challenge and providing equipment suitable for scale-up and industrial microwave firing. University researchers, microwave manufacturers, and independent microwave testing facilities can be used to develop process know-how and for assistance with scale-up challenges.

1.5. Problem Statement

In wood based industry, the shortage of wood as a raw material has become eminent recently. It was estimated that at least 20 million of solid wood is used in wood based industry each year (Abdul Khalil *et al.*, 2010). The lack of wood resources has been considered as a serious problem in wood industries. Not only limitation in resources, but also vast consumption of wood made the research vital to replace alternative materials. New sources including waste material could be developed to achieve wood properties. Oil palm biomass appear to be the most viable alternative especially oil palm trunk which is possible to be utilized as value added product in wood-based industry (Mohamad *et al.*, 2005).

The amount of biomass produced by an oil palm tree, inclusive of the oil and lignocellulosic materials, is on the average of 231.5 kg dry weight/year. As such, the oil palm industry should utilise the available biomass (Yusof, 2007). For the disposal of oil palm stems, they were 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 stern 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* (Lim and Gan, 2005). Disposing of oil palm stems by burning is not acceptable due to environmental concerns. The implementation of zero burning technique for replanting on a commercial scale (Mohd Hashim *et al.*, 1993b) and in new plantings (Jamaludin *et al.*, 1999; Ramli, 1999) has been a major factor in minimizing air pollution by plantations. To preserve a clean environment with the vision of zero-waste strategy, research and development activities are converged on the utilization of oil palm biomass such as empty fruit bunches (EFB), oil palm fronds (OPF) and oil palm trunks (OPT). Insufficiency of wood lumber and potential for transforming oil palm trunk waste to an alternative wood lumber material make this research indispensable to discover the most appropriate ways of utilising this expected large amount of oil palm trunk agro waste.

Commonly the bark and the outer region of oil palm trunk were removed and utilized but the core part has been totally waste so far and due to the chemical composition can only be converted to cattle feed (Tomimura, 1992). Various drying methods may result in different mechanical and physical properties. The ordinary drying method for oil palm trunk is kiln drying. Recently researchers have been working on drying with microwave due to more qualified results. Yet, there are so many aspects which require more investigation (Abdul Khalil *et al.*, 2009; Shulman and Alfred, 2003). This study optimized the microwave drying conditions of oil palm trunk core part for the first time and enhanced a more complete drying, avoid burning, shrinkage and swelling and increase the permeability of OPTCL. The main novelties of this study are applying microwave and utilizing core part of the oil palm trunk.

Resin impregnation to wood has applied for dimensional stability enhancement and prevention of biodeterioration as wood-preservation technique (Furuno *et al.*, 2004). Due to the low mechanical and physical properties of oil palm trunk agro waste, it could be modified with low molecular weight phenol formaldehyde (PF) to gain higher characteristics(Shams MI and Endou, 2004). Formerly scientists made studies to improve the properties of oil palm trunk such as dimensional stability, durability and strength (Bakar et al., 1999; Bhat et al., 2010; Edi Suhaimi et al., 2008).

The heartwood of most species resists penetration of preservatives, but for well-dried species it is reasonably easy for resin to penetrate (Forest Products Laboratory, 1999). Proper microwave drying and precise impregnation technique modified the core part in this study. Whereas, new oil palm trunk exhibit superior and good permeability through modification with microwave technique compared to kiln dry treatment. For impregnation process phenol formaldehyde which is a thermoset resin was chosen. The main reasons were its low viscosity, low volatility, lack of odor, low toxicity, less heat generation at polymerization, and low price (Abdul Khalil *et al*., 2007a; Abdul Khalil *et al*., 2007b; Khoo and Lee, 1985).

1.6. Objectives

This research project is planned and carried out to address the following objectives:

1. To optimize the drying conditions of oil palm trunk core lumber (OPTCL) using microwave and developing a model to predict the drying parameters and compare with oven drying.
2. To fabricate and investigate OPTCL impregnated with phenol formaldehyde at different time of resin impregnation.
3. To study physical, mechanical and thermal properties of new product and compare them with impregnated kiln dried lumber and Rubberwood properties.

4. To study the morphology of resin impregnated OPTCL.

1.7. Scope of Study

In this study, the main purpose is to develop the core part of oil palm trunk agro waste, which is readily available in Malaysia into a value added material. The significance innovation of this study is microwave drying the core part of oil palm trunk which contains less vascular bundles and more parenchyma. Microwave drying with proper selection of power input from 660 to 3300W, 500–1000 ± 5g drying material weight and drying time within 2-10 min was investigated in this study. A comparison was made between microwave drying with and without pre-air drying. A set of experiments were designed by central composite design using response surface methodology (RSM) to statistically evaluate the findings. The independent process variables were time (2-10 min), OPT concentration (500-1000g) and input power of the microwave (660-3300W). This study aimed to optimize the drying conditions using microwave to enhance a more complete drying, avoid burning, shrinkage and swelling and increase the permeability. In the preliminary study on microwave drying, the moisture content of OPT core part reduces from 294% to 12–15%, which is within the optimum moisture content.

The modification of wood with phenolic resin also has been done to improve the dimensional stability and biological exposure. Moreover, using low molecular weight of phenol formaldehyde (PF) has been studied to gain better wood characteristics. In this study different impregnation times applied for OPTCL were 15, 30, 60, 90 and 120 min. The mechanical and physical test results for oil palm trunk core lumbers (OPTCLs) dried with microwave were compared with the

OPTCL dried with kiln. Mechanical properties of impregnated oil palm trunk core lumber were tested for tensile strength and modulus of elasticity (MOE), flexural strength and modulus of rupture (MOR), compression strength and impact strength. All the samples were tested based on BS EN 373:1957 methods of testing small clear specimens of timber except for impact strength that was tested according to ASTM D256. SEM results illustrated resin fully penetrated into the OPTCL structures. According to the test results, on average the properties of microwave dried samples were higher than kiln dried ones.

1.8. Organization of Thesis

This thesis contains five main chapters. The first chapter (Introduction) will briefly introduce the research project, the problem statement, and the scopes of the study. In the Literature Review section (Chapter 2), an overview of the reported results related to this study and the main basic knowledge about this project such as microwave applications, impregnation process and others are discussed in detail. Chapter Three (Material and Methods) includes descriptions on the materials, experimental procedures and instrumental analysis used in this project. The response surface methodology (RSM) designs used including the ranges and the codes are introduced and discussed in this section. This chapter is presented in great detail and arranged in such a way that it can be easily repeated by other researchers. Results and discussions made in this project are given in Chapter Four. This chapter includes different parts such as microwave drying of OPTCL, optimization of the drying conditions, physical and mechanical properties of the impregnated OPTCL. In Chapter 5 (Conclusions and Recommendations), overall conclusions based on results and findings made in the present study are given in brief. The recommendations for future research based on the understanding and knowledge generated in the present study are also given in this chapter.

CHAPTER 2

LITRATURE REVIEW

2.1. Oil Palm in Malaysia

The oil palm is a tropical palm tree originated from West Africa. The great expansion of this crop has increased very rapid during the last two decade in many parts of the world, such as Africa, the Pacific Islands, South America, and especially in Southeast Asia, with Indonesia and Malaysia as main producers. The first commercial oil palm estate in Malaysia was set up in 1917 at Tennamaran Estate, Selangor (Sumathi *et al*., 2008). Favorable climate in Malaysia caused the increasing growth in oil palm cultivation. The oil palm is mainly grown for its oil production and its economic life spans is about 25 years. There are two main oil products which can be obtained from its fruit: crude palm oil (CPO) and palm kernel oil (PKO). These palm oils are used in a great variety of products, both edible and non-edible products. Palm oil is being one of the main sources of cooking oil, shortening, ice creams and margarine, as well as being used in non-edible products such as detergents, soaps, shampoos, lipsticks, creams, waxes, candles and polishes. In advance, it is used as a lubricant in industrial processes and also yields olein used in chemical processes to produce esters, plastics, textiles, emulsifiers, explosives and pharmaceutical products(Erwinsyah, 2004).

The development of palm oil production produces bio-waste in two forms: waste from mill and waste from plantation. The waste from mill consist of shell, empty fruit bunch (EFB), pressed fruit fibres (PFF), palm oil mill effluent (POME), whilst the other wastes from the plantation comprises of oil palm fronds (OPF) and oil palm trunks (OPT) during replanting after achieving its economic life spans

(Erwinsyah, 2004). Since the last decade, the producers of oil palm, particularly Indonesia and Malaysia have been facing a serious task concerning the utilization of oil palm solid wastes both from the mill and plantation, particularly EFB and OPT. The spectacular amount of natural solid waste is a great potential for biomass resources, such as fibre, cellulose as well as raw material for substituting wood material from natural forest. The oil palm planted area in Malaysia is 4.48 million hectares (Singh *et al.*, 2010) produces 15.9 million tonnes oil and with more than 70 000 hectar of oil palm plantation, felling of about 9 million palm tree is required every year for replantation (Mokhtar *et al.*, 2008).

The number of oil palm trunks (OPT) available after replanting activities at any time is enormous and has been estimated that felling in Malaysia yields approximately 85 tons of stem per hectare (Haslett, 1990). An oil palm tree is showed in Plate 2**.1**

Plate **2**.1 Oil palm tree (Abdul Khalil *et al.*, 2006)

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 difficult. For the disposal of oil palm stems, they are normally left to rot or are burnt in the field. The most common method for replanting oil palm was the *push-felled and burn* method in order to reduce the mass and volume.

Push-felled was done by the excavator or other heavy vehicles. The *zero burning* program which was introduced in the 90's, immediately banned, because of the air pollution it created. Further, the push-felled methods followed by burning process was modified into the new method called *push-felled and windrow*. To increase the degradation process by natural decomposer, after pushing and felling, the palms were chipped into pieces. The chipped of the palms were not burnt but then windrowed, this method named *push-felled, chip and windrow*. Most of the oil palm companies, currently applies this method. It may look quite effective, but it was also reported that the attacks by pests and diseases increase very rapidly to the young mature plants around the replanting area. The chipped palms became nests of rat and beetle and also as media for *Ganoderma* disease.

The other zero burning technique of replanting program was the *under-planting* method, where the young palms were planted under the old palms, which were gradually poisoned. Unfortunately, the poisoned palms took more than two years to decompose completely and this resulted in very high breeding of *Oryctes rhinoceros* beetles, which has become the most serious pest in immature and young mature palms. In fact freshly felled stems with their high moisture content cannot be easily left or burnt in the field. Leaving the stems in the field without further processing will serve breeding grounds for insect pests. The high susceptibility of oil palm stem to infestation by both fungi and insects are due to the presence of high sugar and starch in the parenchyma cell wall (Lim and Gan, 2005).Burning oil palm stems is also unacceptable as it highly pollutes the air (Jamaludin N. et al., 1999; Lim and Gan, 2005; Mohd Hashim et al., 1993a). The most environmentally friendly cure for the mentioned problem is to utilize the trunks almost directly after cutting and the trunks could be moved from the replanting area for further processing. This only happens when the appropriate recovering method for the waste trunk becomes clear. Plate **2**.2 and Plate 2.3 demonstrate a view of replanting process.

Plate **2**.2 Replanting process

Plate 2.3 Trunks which are fell for replanting

The chemical, physical and mechanical properties of the oil palm biomass including oil palm trunks (OPT), oil palm fronds (OPF) and empty fruit bunches (EFB) indicate that these materials are similar to wood, and they may be suitable raw materials for wood based panels(Abdul Khalil *et al.*, 2008). Intensive research work in generating technologies to convert OPF and OPT for the manufacture of commercially viable composite panel products have also proven to be successful in most cases.

The production of medium-density fiberboard, particleboard (Chew, 1987) and cement-bonded particleboard (Kochummen *et al.*, 1990), fiber reinforced cement board (Abraham *et al.*, 1998), fiber plastic composite (Liew *et al.*, 2000) and plywood (Ho *et al*., 1985) from OFB and OPT have shown to be technically feasible. The production of blockboard (Mohamad *et al*., 2001) as well as furniture (Mohamad *et al.*, 1989) from OPT lumber have also been investigated with promising potentials (Mohamad *et al*., 1989; Nordin *et al.*, 2004). Palm oil biomass can be utilized to produce various types of value added products. For instance 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. 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 particleboards, bonded with resin. The denser material from the base of the trunk can be used to make furniture after treated with suitable resin (Sumathi *et al.*, 2008). Several of these applications have been tested successfully in the materials have been produced (Koh *et al.*, 1999).

On the contrary, the oil palm solid waste, particularly the OPT, has received relatively little research attention. This might be due to lack or insufficient the scientific information of this material and might also be due to the difficulties of working and using OPT. Although several investigations have already conducted in the field of OPT uses, but a sufficient knowledge shall be achieved in order to design and establish the new wood products based on oil palm wood (Wood here is primary tissue and is not comparable in developmental term to the wood of dicotyledons and gymnosperms, because palms do not possess cambium) (Erwinsyah, 2008).

With the decreasing supply of raw materials from traditional sources such as Rubberwood and tropical hardwoods, utilizing of oil palm trunk (OPT) as an alternative lignocellulosic raw material for wood based industry should be considered. The main obstacle of utilization oil palm trunk (OPT) is that it is a monocotyledon plant 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.*, 2004). In fact OPT is not wood as what the wood-based industries are used to.

The palm trunk structure is not strong enough for use as lumber, and thus, only the outer part of the trunk, which is relatively strong, is partially utilized for plywood manufacturing. In the plywood production process, the inner part is discarded in large amounts due to its weak physical properties (Kosugi *et al.*, 2010). Researchers in several countries discovered the novelty of oil palm stem material in the field of timber utilization (Shaari *et al*., 1991). Regarding the unique characteristics it is not easy to process or to work with. Since 2000 the Forest Products Research and Development Center (FPRDC) has created new approach in timber processing through application of several organic and inorganic modifications to improve low density timbers and the oil palm wood. The procedure established a promising prospect of using OPT stem as substitute material for production of furniture and building components (Balfas, 2006).

Some of the natural characteristics of OPT are the main challenges to transfer it to a manageable raw material for producing various product. The parameters that make difficulties in utilizing OPT are as follows:

- High moisture content and variation in density (Lim and Gan, 2005).
- High decay and insect susceptibility
- Rapid degradation when left without proper treatment after felling.
- Inconsistent physical properties along the trunk
- The extreme saw blunting properties due to the presence of silica in OPT structure (Haslett, 1990).

Oil palm lumber has been successfully utilized as core in the production of block-board. 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. The saw-wood produced from oil palm can be used to make furniture but not for building structure due to its low specific density. Nevertheless, the strength of the ply-wood produced from oil palm was found to be comparable with commercial ply-wood (Sumathi *et al*., 2008).

The Forest Research Institute Malaysia (FRIM) has been seeking to develop oil palm trunk use in four ways: 1) Derivation of cattle feed; 2) Liquid fuel extraction; 3) Development of sawmill and process to produce sawn timber; and 4) wood based panels production (Haslett, 1990). Oil palm trunk also has been used to produce particleboards with chemical binders.

2.2. Characteristics of Oil Palm Trunk

2.2.1. Physical Properties of Oil Palm Trunk

Usually the trunk ranges between 9 to 12 meter in height and 45 to 65 centimeter in diameter (Husin *et al.*, 1986). The main physical properties are moisture content, density and fiber dimension which are described separately in the following sections.

2.2.1.1. Moisture Content

The moisture content in green condition can be reached more than 500 % with the average value of 304%. Compared to wood timber with normally 40 % and 50 % moisture content, oil palm trunk contains far more moisture. The high quantity of sap in the inner part of the trunk causes an extremely high level of moisture (Kosugi *et al.*, 2010). The moisture content is gradually increased from the bottom to the top of the trunk and from outer part toward the central point(Choon and Khoo, 1986). The main reason for the decrease in moisture content from the bottom to the top of oil palm tree is expected to be the effect of gravity (Bakar *et al.*, 1999). When there is an increase in the number of vascular bundles, the percentage of parenchyma cells which have high capacity in water absorption decrease (Prayitno, 1995). Moreover the volumetric shrinkage was gradually increased from the bottom to the top of the trunk and it varies between 10.3% and 22.8% (Erwinsyah, 2004).

2.2.1.2. Density

Oil palm trunk does not demonstrate clear pattern in density variation (Husin *et al.*, 1986). Due to OPTs 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 as demonstrated in Figure 2.1(Choon and Khoo, 1986). This is reflected 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 of the inner regions. The density at inner and central zone was about 0.18 g/cm^3, ranging from 0.17 to 0.23 g/cm^3, respectively. While the density at peripheral zone was about 0.40 g/cm^3, ranging from 0.37 to 0.43 g/cm^3. The density value was gradually increased from inner to peripheral zone, but it was slightly decreased from the bottom to the top of the trunk. The wood zoning factor has more effect on the wood density of oil palm than the trunk height factor.

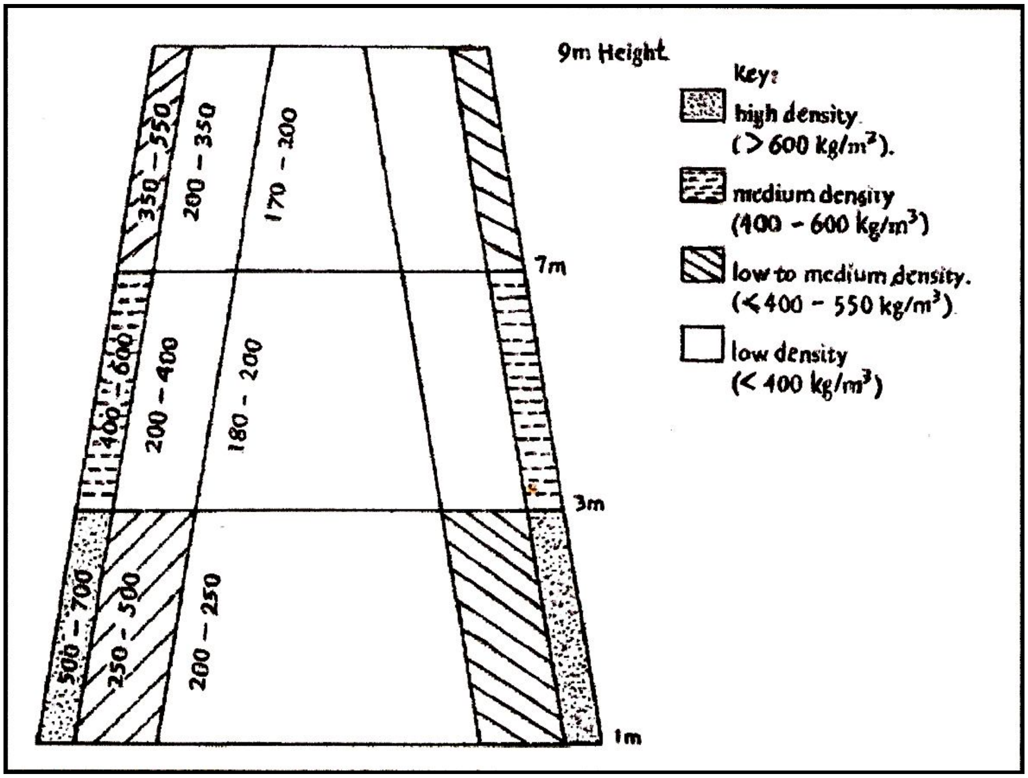

Figure 2.1 Schematic diagram of density variation in oil palm stem (Choon and Khoo, 1986)

Considering this characteristic it is recommended to use the trunk parts separately, both from outer to inner part and along the trunk. The 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 of the palm. Although higher in number per square centimeter, the bundle here are smaller in size and the cell walls are thinner. Higher density values in the peripheral zone are also due to the following reasons:

- Presence of radials extended fibrous sheaths.
- Less number of vessels and general absence of extended protoxylem in the outer vascular bundles.

- Progressively thicker walls of the ground parenchyma cells from the inner to the outer zones.
- Presence of better developed secondary walls in the fibers (Choon and Khoo, 1986).
- The oil palm trunk can be use as wood construction until 2/3 from the outer part across the trunk and the other 1/3 part can be used for making house tools (Sadikin, 1986). Based on the low average specific gravity and the density gradient along the radial and longitudinal directions of the trunk indicate that OPT may not be suitable for structure dimension lumber like other forest wood (Husin *et al*., 1986).

2.2.1.3. Fiber dimension

The primary variables that determine the overall properties of the fibers are structure, microfibrillar angle, cell dimensions, defects, and the chemical composition of fibers (Maya and Sabu, 2008). The dimensions of individual cells in natural fibers depend on the species, maturity and location of the fibers in the plant and also on the fiber extraction conditions. In all lignocellulosic fibers unit cells have a central hollow cavity called Lumen. The size and shape (round, polygonal or elliptical) of the lumen depends on the thickness of the cell wall and source of the fiber.

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) (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 fiber length increases from periphery to the inner part. Mean fiber 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 (Choon *et al*., 1991).

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 2.1.

Table 2.1 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	-

Oil palm wood fibres 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 fibres 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, 1985). The fibre diameter decreases along trunk height because broader fibres are to be found in the larger vascular bundles nearer the base of the palm trunk and vice versa. Oil palm fibres are comparable in length to fibres from Rubberwood, but are much shorter than those of Douglas fir (Choon *et al.*, 1991).

2.2.2. **Chemical Composition of Oil Palm Trunk**

Yusof *et al.* stated that 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). Besides, Husin *et al.* found that the lignin and lignocelluloses content of OPT is lower than coconut wood and Rubberwood but shows higher content of extractives, as well as water and alkali soluble (Husin *et al.*, 1985). Five years later Halimahton and Ahmad observed that the lignin content was evenly distributed throughout the trunk except the core in the upper region which was scarce in the component whilst the bottom contained massive amount. The lignin content range varies from 15% to 21.7%. The result 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 (Halimahton and Ahmad, 1990).

The ash content also was found to be similar throughout the trunk with the range varies between 3.0 % and 3.3 %. Ash and silica contents were found high value at the inner zone. The soluble analyses using hot water, cold water, alcohol benzene and NaOH 1 % were also found high proportions at the inner zone. Important contribution of the further development of the chemical properties of oil palm trunk were studies of free sugar and starch carried out by (Sudin *et al.*, 1987). Freshly felled oil palm trunk may yield up to 10% free sugars and 25% starch. Furthermore, (Halimahton and Ahmad, 1990) reported that a 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 (Erwinsyah, 2008). 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 present 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 %). The main chemical composition of oil palm trunk is tabulated in Table **2**.2 and each of them are explained completely (Abdul Khalil *et al.*, 2008; Tsoumis, 1991).

Table **2**.2 Chemical composition of oil palm trunk, coconut trunk and bamboo (Abdul Khalil and Rosman, 2004)

Composition	Extractive (%)	Cellulose (%)	Holocellulos (%)	Lignin (%)	Ash (%)
Oil palm trunk (OPT)	5.35	41.02	73.06	24.51	2.4
Coconut trunk	6.4	43	56.3	45	2.2
Bamboo	6.62	25.3	71.40	28.76	1.3

2.2.2.1. Cellulose

Cellulose as the main component in lignocellulose fibers is the reinforcing material in 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 2.2. 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 collaborated with extensive hydrogen bonding. These networks form the microfibril which produces a strong crystalline structure as a reinforce fundamental in the cell wall.

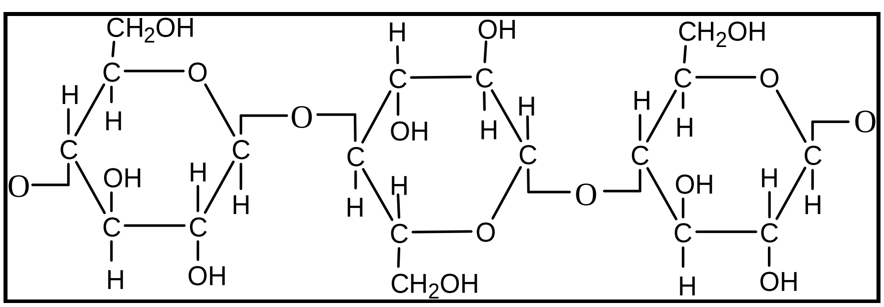

Figure 2.2 Molecular structure of cellulose (Tsoumis, 1991)

The microfibrils have associated with them crystalline and amorphous components with associated OH groups. Since the nature of the microfibrils is crystalline, the cellulose component is relatively thermally stable and not reactive