OIL PALM LUMBER WITH BIORESIN TREATMENT

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Oil Palm Lumber with Bioresin Treatment

An inspirational book for the oil palm industry

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Table of Content

Preface

First of all, all praises to Allah S.W.T. who gives me strengths, comprehensions, and His blessings in completing this book. I would also like to express my deep gratitude to my co-supervisor, Dr. Kamarudin Hassan (MPOB), and Dr. Abdul Rahman Hassan (USIM) for his and assistance in keeping my progress on schedule regarding this book.

This book contained 6 chapters which begin with Chapter 1 as an introduction to the topic of the book. Next, Chapter 2 discusses the wood-based and the oil palm industry in Malaysia. The detail about the wood and the treatment of the wood are described in Chapters 3 and 4. Lastly, the impregnation approach is discussed in Chapters 5 and 6.

Sincere thanks to all my friends especially my beloved wife Ngalo Putri Ginting and also friends Aisyah, Sabri, Nadrah, Anis, Bangah, Razlan, Zuhair, Faisal, Yohana, Asyrof, Zulhilmi, Halim, and others for their kindness and moral support during my study. Finally, I wish to thank my parents, Dr. Badrul Munir M. Nur and T. Asmah Zatun Matabin also to my siblings namely Maryam, Muhammad Abdurrahman, Ahlam Inayatullah, Abdul Jawwad, Tahani, Dalaal Mahmudah, and Ahmad Abdul Aziz for their support and encouragement throughout my study.

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List of Figures

List of Equations

Chapter 1

Introduction

The timber resource scenario, particularly in Peninsular Malaysia has changed in many respects during the last ten years and continues to change. In the past, the wood-based industries were blessed with having abundant quantities of high-quality wood from natural forests. The wood with excellent desirable characteristics was naturally "ready to use" requiring little processing effort. However, the supply of these timbers has become scarce and no significant supply can be expected from the natural forests in the year to come (Forestry Department Peninsular Malaysia, 2013). Uysal (2005) mentioned that the shortage in timber supply from the natural forests was due to the expansion of new plantation areas for agriculture crops while Alan and Miller (2000), addressed this issue about illegal logging.

Hence available timber is now generally smaller in diameter and lowers in quality than before. Many species that are deemed undesirable in the past are now being used because of a shortage of more desirable species of timber. Due to high demand and short supply, the prices of timber, particularly for the production of sawn timber have increased rapidly and continue to increase (Forestry Department Peninsular Malaysia, 2012). Table 1.1 shows the amount of log production from the natural forests for respective countries. Thus the dependence of wood industries on fast-grown plantation species as the main source of wood is predicted to significantly increase in the coming year (FAO, 2009).

Apart from forest plantations, another one that responds to this situation would be to utilize the lignocellulosic of agriculture biomass that includes the felled oil palm trunk (OPT) and rubber tree for some products that have traditionally been made from wood (Salman, 2015; UNEP, 2012). Based on the hectarage of oil palm planted in 1991/1992 and the planting density of 136 palms ha^{-1}, the availability of felled oil palm trunk (OPT) is estimated at 23 million m^3 y^{-1} in the year 2017 to 2018 (Kamarudin *et al.*, 1997). Thus the quantity at hand could act as an alternative raw material to wood to satisfy increasing timber demands from the natural forests or forest plantations.

Table 1.1: Estimated amount of log production from a natural forest of main exporting Asia-Pacific countries (millions m^3)

Countries	Year (million m^3)	
	1998	2010
Malaysia	22	12
Indonesia	40	15
Cambodia	3	1
Papua New Guinea	2	2
Solomon Island	1	0
Total	68	31

Source: Joakko and Ogle/Miller estimates (source from Alan and Miller, 2000)

The oil palm tree is naturally a variable material (Tomlinson, 2006; Hodel, 2009; Tomlinson and Quinn, 2013), and therefore, the physical and mechanical properties of the tree trunk are far from homogeneous (Killmann and Lim, 1985; Lim and Gan, 2005; Paridah and Anis, 2008; Kamarudin *et al*., 2011). Like fast-growing forest plantation logs such as *Acacia mangium* (acacia tree) (Krishna *et al*., 1998) and *Hevea brasiliensis* (rubber tree) (Kollert and Zana, 1994; Teoh *et al.,* 2011), the conversion of OPT to oil palm lumber (OPL) has to be carried out immediately, as long-term storage may not be economical (Ratnasingam and Scholz, 2012). This is to prevent insect and fungal attacks (Ho *et al*., 1985; Koh *et al*., 2009) due to high moisture and starch contents (Halimahton and Abdul Rashih, 1991; Nur Syuhada *et al.,* 2011; Anis *et al.,* 2011).

The biggest challenge is attributed to the small diameter of OPT, which makes its handling and sawing difficult compared to large-diameter natural forest saw logs. For OPT, the form and sizes rarely exceed 500 mm in diameter at breast height (DBH) when delivered to sawmills (Edi Suhaimi *et al*., 2006; Anis *et al*., 2007). Therefore the most common sawing operation to convert OPT into sawn lumber is the live-sawing (also called "through and through" sawing) technique (Ho *et al.*, 1985; Anis *et al.*, 2007; Koh *et al.,* 2009). This method does not require any turning of the OPT, nor special skill in making the cutting decision. It is the fastest conversion method compared to other widely used sawing patterns such as sawing-around, cant-sawing, and quarter-sawing (Todoroki and Ronnqvist, 2002).

Since the cutting of OPT does not consider pieces of sawn lumber with defects, the gross sawing yield is highly reduced due to the development of seasoning defects (Ho *et al.*, 1985; Anis *et al.*, 2007) such as are collapse, warping, and checks (splits) between vascular bundles and parenchymatous tissues (Koh *et al.*, 2009; Zabler *et al.*, 2010). This might be the result of the cutting pattern used, which is mostly cutting through the pith of the OPT. In general, the OPL cut through the pith of the OPT contains a mixture of higher-density juvenile material in the outer parts together with a lower-density juvenile material in the middle piece (Anis *et al.*, 2007). Hence the live-sawing technique is most suitable for less defective and large diameter logs from natural forests (How *et al.,* 2007).

Juvenile material in oil palm trees may be described as a zone developing around the pith continuing towards the outer perimeter where its characteristics and properties are subject to gradual changes (Zobel and Sparague, 1998). Consequently, a sawn lumber containing the juvenile woody material tends to give excessive distortions due to the occurrence of differential shrinkage during drying (Maeglin, 1987).

Despite their availability and research findings, the commercial use of OPT for sawn lumber and biocomposite products has yet to reach the desired level. The OPT has a high amount of parenchyma tissues (Halimahton and Abdul Rashih, 1991; Kamarudin *et al.*, 1997; Henson *et al.*, 1999; Nur Syuhada *et al.,* 2011; Anis *et al.,* 2011), and therefore, drying distortions of untreated lumber seemed to be unavoidable (Ho *et al.,* 1985). This will reduce the utility and value of products (Koh *et al.*, 2009). Most of the defective OPL pieces were those from the central region. Therefore, in the seasoning of oil palm lumber, the boards from the peripheral zones of the trunk have to be separated from the central region and the use of a fast kiln-drying method for lumber drying (Koh *et al.*, 2009). Drying boards from both peripheral and central zones of the oil palm trunk decreases the overall percentage of sound timber (Anis *et al.*, 2007).

Some of the OPT properties, in particular dimensional stability and durability, are inferior compared to wood (Koh *et al.*, 2009). Dimensional instability, low mechanical properties, and low durability have put it at a disadvantageous position in the competitive market. For OPT, the commercial value is determined by complex interactions between the variations in physical and mechanical properties from butt to crown (Lim and Gan, 2005; Paridah and Anis, 2008), site location, and growth characteristics (Cown and Parker, 1978; Morris *et al.*, 1997), processing (Ho *et al.*, 1985; Edi Suhaimi *et al.,* 2006; Kamarudin *et al.*, 2006), and the demands of the market (MPMA, 2007).

Without chemical pretreatment, the OPL is generally susceptible to biodegradation agents such as fungi and wood borers (Ho *et al.*, 1985; Lim and Gan, 2005; Milling *et al.*, 2005). Besides, OPL when exposed to cyclic humidity changes is subjected to unequal expansion in the tangential and radial directions (Sulaiman *et al.*, 2012). This creates internal stresses, which can result in distortion such as checking, warping, and twisting (Larson *et al.*, 1983). The dried OPL has a low density and subsequently gives lower mechanical properties (Sulaiman *et al.*, 2012). This reduces the utility and value of finished products as furniture parts (Ratnasingam and Ioras, 2010).

Sawn lumber is generally treated with chemicals in the form of water repellents and/preservatives to protect it against moisture fluctuation, microorganisms, and ultra-violet (UV) rays to improve its dimensional stability (William and Feist, 1999). However, certain chemicals used in traditional water repellents and preservative solutions, such as pentachlorophenol (PCP), copper-chrome-arsenate (CCA), and creosote are toxic to mammals and harmful to the environment (Cooper *et al.*, 2001).

These developments have resulted in significant researches and commercial interest in wood modification technologies such as oil palm stem densification (Killmann and Koh, 1988) and chemical modifications (Robert *et al.*, 2009). The improved characteristics of modified lumber offer many potential and attractive opportunities for the wood industry (Homan and Jorissen, 2004). Hence new methodologies need to be developed to process the readily available OPT for sawn lumber productions.

Improvements in the lumber quality through a lower rate of dimensional shrinkage during seasoning, and the physical and strength properties of resulting lumber in an environmentally benign way is one of the biggest challenges but also an opportunity for wood technologies. For the resin impregnation of a rosin-gum, an innovative vacuum infusion (VI) system, which is specially designed and built for oil palm lumber, was used in this book.

The objectives of the book are three; 1) to investigate the loading of gum rosin within the OPL matrix by a vacuum infusion technique, followed by a densification process while maintaining its integrity, 2) to determine the dimensional changes of densified rosin-treated OPL samples to provide a preliminary assessment of lumber shrinkage, both in radial and tangential planes and to evaluate the strength properties of densified rosin-treated OPL in relation of matched untreated OPL samples.

Chapter 2

The Wood-based Industry in Malaysia

In general, the wood-based industry is comprised of four major sub-sectors, namely (a) sawn timber, (b) veneer and panel products such as plywood, particleboard, chipboard, and fiberboard, (c) wooden moldings, and (d) builder's joinery and carpentry (BJC) such as doors, windows, flooring board, parquet and furniture (MIDA, 2012). Malaysians predominantly own the industry where 80% to 90% of the companies comprising of small and medium-size establishments (Department of Statistics Malaysia, 2013).

In 2014, these commodities were exported to Japan valued at RM 4,154.56 million, United States of America at RM 2,422.80 million, India at RM 1,771.05 million, Taiwan at RM 988.21 million, the Republic of Korea at RM 954.34 million, the Republic of Singapore at RM946.87 million, Australia at RM905.23 million, the People's Republic of China at RM 788.06 million, United Kingdom at RM 758.46 million and other countries accounted the remainder RM 6,830.07 million. Thus this industry had successfully contributed a portion of foreign exchange needed to bring about the social and industrial development of the country (MTIB, 2015).

Like in most countries, the development of wood-based industries in Malaysia tends to follow a similar pattern, starting with log production first and gradually getting involved in sawmilling and plywood manufacturing and finally in downstream processing such as the production of joinery, furniture, and others (MIDA, 2012). Compared to Sabah and Sarawak, the wood-based industries in Peninsular Malaysia have started to develop much earlier and hence its resources have already been considerably exploited (Forestry Department Peninsular Malaysia, 2013). Thus most of the downstream processing mills mainly utilized rubberwood, which is sourced from sustainable plantations as raw materials for furniture and panel products (MPIC, 2009).

Forest resources

Malaysia has a total land area of 330,290 km^2, of which 18.1 million ha (about 60.8%) are under forest cover. It is separated by the South China Sea into two regions, Peninsular Malaysia and East Malaysia (Sabah, Sarawak, and Federal Territory Labuan). If areas under rubber, oil palm, cocoa, and coconut are taken into consideration, more than 73% of the country can be reckoned to be under some sort of tree crop. The forested areas in Peninsular Malaysia, Sabah, and Sarawak in 2012 are given in Table 2.1 (Department of Statistics Malaysia, 2013).

Table 2.1: Hectarage of forest land area for Peninsular Malaysia, Sabah, and Sarawak in 2012

Region	Forested Areas (ha)	Area of Permanent Forest Estates (ha)
Peninsular Malaysia	5,788,523	4,893,613
Sabah	4,435,990	3,609,249
Sarawak	7,886,500	4,546,096
Total	18,091,013	13,048,958

(Source: Department of Statistics Malaysia, 2013)

Of the 18.1 million hectares of forest, dipterocarp forest, amounting to 16.5 million ha, is the most important forest type in Malaysia. The peat swamp and mangrove forests cover an area of 1.07 and 0.54 million ha, respectively. By the concept of rational land use (Birka *et al.,* 2011), permanent forest estates (PFE) have been established in the three regions. The status of PFE is given in Table 2.2 (Forestry Department Peninsular Malaysia, 2013).

Table 2.2: Hectarage of permanent forest estates for Peninsular Malaysia, Sabah, and Sarawak in 2012

Region	Protective (million ha)	Production (million ha)	Total (million ha)
Peninsular Malaysia	1.90	2.85	4.75
Sabah	1.40	3.24	4.64
Sarawak	0.50	2.85	3.35
Total	3.80	8.94	12.74

(Source: Forestry Department Peninsular Malaysia, 2013)

The Forestry Department Peninsular Malaysia, Forestry Department Sabah, and Forestry Department Sarawak are continuing to face great challenges in increasing and sustaining the coverage of PFE in line with the current rapid development in the country (MPIC, 2009). However, the close cooperation between the Federal and State Governments has enabled these Forestry Departments' commitment to conserving the country's forest resources for the benefit of the present and future community's livelihood (Birka *et al.,* 2011).

Timber supply outlooks in Peninsular Malaysia

On a regional basis, Peninsular Malaysia has a land area of 13.18 million ha, of which 5.78 million ha or 43.0% are under tree crops in 2012. Of the 5.78 million ha, 4.89 million ha or 84% have been gazetted as Permanent Reserved Forests (PRFs) under the National Forestry Act, 1984 (Forestry Department Peninsular Malaysia, 2013). These PRFs are managed under the Sustainable Forest Management (SFM) practices for environmental, economic, and social benefits. From the annual report (Forestry Department Peninsular Malaysia, 2013), the forestry sector had provided direct employment of 71,763 persons in the various industries as follows; forest harvesting of 5,997 persons, sawmills of 17,796 persons, veneer and plywood mills of 4,271 persons, moulding plants of 3,762 persons, furniture factory of 34,635 persons and public service of 5,302 persons in 2012. This registered an overall increase of 2.0% as compared to 70,342 persons in 2011.

Inevitably, the present rate of log production is not being able to maintain the wood-based industry in Peninsular Malaysia (Forestry Department Peninsular Malaysia, 2013). The shortfall is partially compensated by logs from the rubber plantations and later from the forest plantations, which are expected to produce logs from the year 2010 onwards (MPIC, 2009). Nevertheless, total log production from natural forests, rubber plantations and forest plantations will stay around 6 million m^3 until logs from the plantations come on stream in a significant way (Forestry Department Peninsular Malaysia, 2013).

The production of solid-wood and reconstituted panel products are the most important of all wood conversion processes (MTIB, 2015). Apart from uncertainties regarding future consumption estimates for developing countries, it is evident that even in countries with a high standard of living and slowly increasing populations, wood consumption is still expanding. Important influences for the future are expected to include (UNEP, 2011):

a) General growth rate in the gross national product (GNP) in the industrial and developing countries, which is known to have a strong influence on wood consumption,
b) Wood production costs, resulting from timber prices, labor costs, energy costs, costs for environmental protection and initial capital investment,
c) Changes in consumer demand and choice of timber types to produce products of different grades for various end uses.

For the manufacture of solid-wood and bio-composite products, the raw material basis is characterized by the increased use of timber from the natural forests and forest plantations (Forestry Department Peninsular Malaysia, 2013). Apart from timber logs, large quantities of untapped natural fiber materials are available from the agricultural sectors. These fiber and biomass materials range from rice husks, coconut trunk fibers, kenaf to oil palm biomass in the form of oil palm trunk (OPT), an oil palm frond (OPF), and empty fruit bunch (EFB). These alternatives raw materials offer vast potentials for development (UNEP, 2012).

The Government encourages industry players to undertake more research and development (R&D) to ensure the reliability of these alternative materials to wood (MPIC, 2009). According to Agensi Inovasi Malaysia (AIM, 2011), this sub-sector had contributed the highest investments in the wood-based industry. Being a current publication about the industry, this report provides strong evidence on the adequacy of resource supply, not only for the solid-wood and bio-composites manufacturing portfolio but also for accommodating other downstream economic activities such as electricity generation (AIM, 2011).

Oil palm industry in Malaysia

As the Malaysian economy continues to expand and develop further, the palm and oil sectors have played an active and important role in the supply of palm oil and palm products as raw materials for the further development of the industrial, commercial, and service sectors. The oil palm tree is the major commodity crop in Malaysia due to the country's Agriculture Diversification Policy to minimize over-dependence on rubber (Yusof, 2000; EPU, 2009; FELDA, 2009) and to the extreme suitability of its climate (Kushairi and Rajanaidu, 2009), is illustrated in Figure 2.1 (MPOB, 2013b).

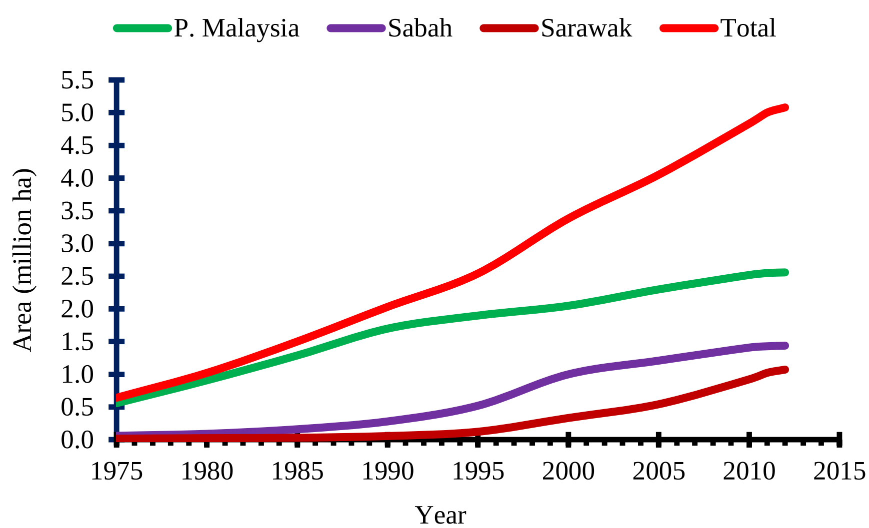


Figure 2.1: Trends of increased oil Palm tree planted hectarage for Peninsular Malaysia, Sabah and Sarawak from 1975-2013 (MPOB, 2014)

The total hectarage of oil palm tree planted area in 2013 was at 5,229,739 ha, a marginal increase of 3.0% or 152,810 ha from the 5,076,292 ha recorded in 2012. The largest area of expansion occurred mainly in Sabah and Sarawak with a combined growth of 4.7% or 117,180 ha compared to the growth of 1.4% or 35,630 ha registered in Peninsular Malaysia. Sabah remained the largest oil palm planted state with 1,475,108 ha or 28.2% of the total planted area, followed by Sarawak with 1,160,898 ha (22.2%), Johor stood at 730,694 ha (14.1%) and Pahang increased by 9,904 ha to 710,195 ha (13.65%) (MPOB, 2014).

Oil palm replanting regime

The height increment of the oil palm tree is very variable depending on both environmental and hereditary factors (Tan *et al*., 1995). Under normal plantation conditions, the oil palm tree of high yielding *tenera* variety grows taller by 40 to 75 cm y^{-1}. The number of fronds produced annually increases between 30 and 44 units y^{-1} (Kushairi *et al*., 2011). After the economic life span of 25 to 30 years rotation (Khalid *et al.,* 2000), the oil palm tree stands are scheduled for replanting with young palms. The zero-burning approach of replanting the oil palm tree that is widely practiced is the clear-felling (chipped-and-windrow) technique and the under-planting method (Mohd Hashim *et al*., 1993; Chia *et al*., 2002). Upon decomposition, the decaying tissues release nutrients to the growing young palms (Khalid *et al.,* 2000). This is a good agricultural practice to save on fertilizer in the next five years, which in turn, would reduce the carbon footprint of the crop (Henson, 1994, 2008; Zulkifli *et al*., 2010).

In the conventional chipped-and-windrow technique, the oil palm trees are pushed down using a backhoe during the replanting operations. After chipping, OPT chips were windrowed in rows (usually two palm rows to one windrow) and left to decompose in the field (Ooi and Heriansyah, 2005). The new young palms are then being planted between the windrows (Khalid *et al*., 2009; Ike *et al.,* 2012). On the other hand, the under-planting method involves the planting of young oil palm seedlings under the old unproductive oil palm trees, which are gradually being poisoned using glyphosate (Chung *et al.,* 1994).

However, the windrowed oil palm biomass and the poison palms would take more than two years in order to complete the decomposition process (Chia *et al.,* 2002). This will result in a very high breeding ground of rhinoceros beetles (*Oryctes rhinoceros*) which has become the most serious pest toward the immature and young palms in Malaysia (Norman *et al*., 2001). The beetle damage could cause crop losses of 40% (Liau and Ahmad, 1991) and 92% (Chung *et al*., 1999) in the first year of harvesting in Malaysia.

Apart from *Oryctes rhinoceroses*, the oil palm biomass could also become the source of *Ganoderma* disease problems (Idris, 2011). The stem density of the oil palm infected by *Ganoderma boninense* disease tends to reduce by 50% compared to healthy stem (Najmie *et al.,* 2011). Moreover, the presence of a large number of big chunks of palm biomass equivalent to 85 t ha^{-1} dry matter impeded field access and hindered replanting operations and subsequent field uptake work. Consequently, the oil palm industry is actively looking for commercial outlets in order to eliminate possible pollution or disposal problems caused by these residues. This will indirectly help to increase the value of oil palm for the farmers (UNEP, 2012).

In 2012, Peninsular Malaysia recorded 65,078 ha or 73.2% of the total replanted area. On the other hand, Sabah and Sarawak were at 23,813 ha of replanted area. Sabah registered the largest replanted area with 21,217 ha or 23.9%, followed by Johor at 19,377 ha (21.8%), Pahang was 15,318 ha (17.2%), and Perak with 9,128 ha (10.3%) (MPOB, 2013a). Jusoh (2013) mentioned that the values of oil palm hectarage that are due to replanting approximately 1.8% of the total oil palm planted area or an average of 90,000 ha y^{-1}. Based on the planting density of 136 palms per ha, this would involve the felling of approximately 12.3 million palms generating more than 21.6 million m^3 of oil palm logs (Kamarudin *et al*., 1997). Thus, the quantities at hand could make a substantial contribution to the production of sawn lumber (Kamarulzaman *et al.,* 2003; Koh *et al*., 2009; Ratnasingam and Ioras, 2010), plywood (Paridah and Anis, 2008; Koh *et al.,* 2009; Loh *et al*., 2010), paper pulp (Khoo and

Lee, 1985; Mohd Nor, 1985; Akamatsu *et al.*, 1987a, 1987b; Hozokawa *et al.,* 1990; MPOB, 1997; Kamarudin *et al.,* 2009), reconstituted boards (Chew, 1987; Khozairah *et al.*, 1991; Kollert *et al.*, 1991; Rahim *et al.,*1991; Abraham *et al.,* 1998; Mohamad *et al.*, 2001) and fiber-based biocomposite products (Mohd Nor *et al.,* 1995; Laemsak and Okuma, 2000) without a need to extract out more timbers from the nation's forest resources.

Characteristics of Oil Palm Stem

The oil palm tree consists of four parts, namely the roots, the stump, the stem, and the crown. The roots are the underground part of the tree that supplies it with nourishment. The stump is the lower end of the tree that is left above ground after the main part has been cut off. The stem is the main ascending axis of the tree above the stump. The crown consists of fronds growing out of the main stem, together with fruit bunch (Hodel, 2009). For solid-wood products, the most important portion of a palm tree, in terms of usable woody material, is the stem (Rich, 1987).

The tree has unbranched axes, each of which supports a terminal turf of appendages (leaves), each leaf supported by a basal sheath. The palm stem represents the reinforced concrete of the structural engineer (Figure 2.2), since its tissues can be thought of as a series of axially oriented vascular bundles (steel rods) embedded in a parenchymatous ground tissue (concrete mix) (Tomlinson, 1990).

Unlike the engineer's reinforced concrete, the vascular bundles of the palm trunk are not necessarily uniformly distributed, but usually concentrated toward the stem periphery for maximum efficiency (Tomlinson, 2006). The stem of many palms has an additional feature, unfamiliar to human engineers, in that it can increase in stiffness with age (Rich, 1987). This is a very efficient way of growing because it means that the palm is not excessively overbuilt. It is as if an engineer could design a structure that becomes increasingly stronger directly as increasing strength is required. If the life span of the structure is shortened accidentally by some factors other than mechanical failure, the initial investment in the aborted structure is minimized. In terms of the palm tree, this 'saved' investment can be diverted to more appropriate ecological events, such as growing in height, or reproduction (Dransfield *et al*., 2008).

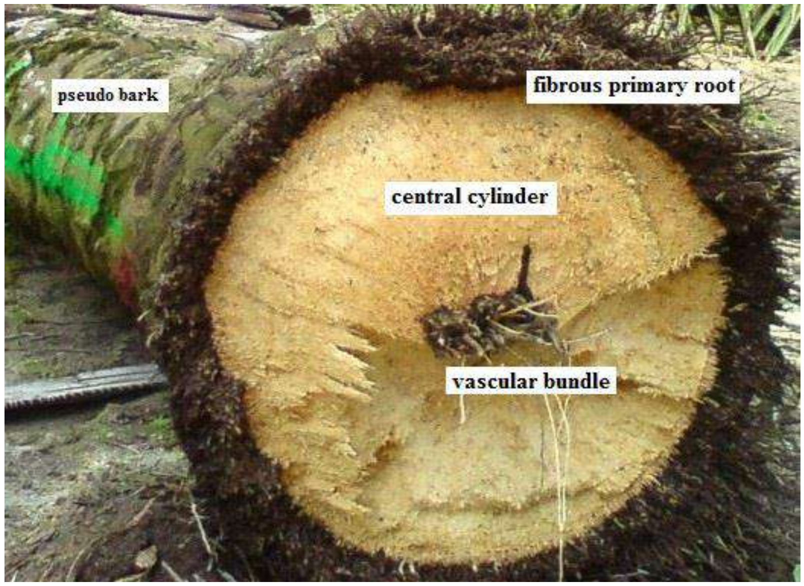


Figure 2.2: Oil palm trunk showing the central cylinder and vascular bundles appears like a strand of wire

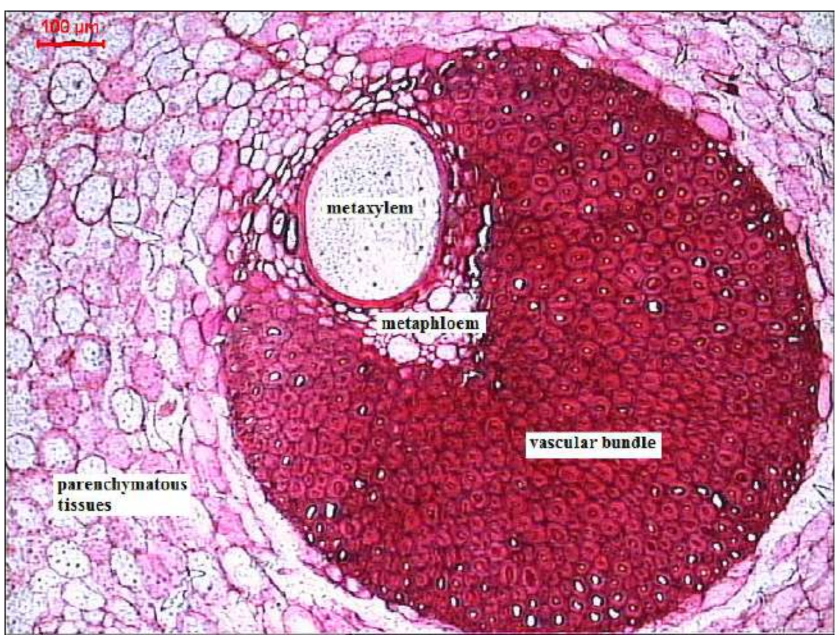


Figure 2.3: SEM photomicrograph of a cross-section of oil palm trunk showing a vascular bundle surrounded by parenchymatous tissues (Loh *et al.,* 2010)

The central ground tissue of palm stems is parenchymatous, but includes specialized cells such as tannin cells and raphide-sacs. Unspecialized cells may be homogeneous, but become lignified with age and contribute to the solid texture of the stem. Otherwise, the ground tissue is heterogeneous and even lacunose, with wide intercellular air spaces so that the tissue becomes quite spongy (Figure 2.3) (Loh *et al.,* 2010). The ground tissue cells may secondarily develop radiating orientation around vascular bundles. Together with widely spaced vascular bundles, this results in the very pulpy central tissue, which contrasts with their peripheral sclerotic layers (Dransfield *et al*., 2008).

A distinctive structural feature is the presence of narrow fibrous strands uniformly distributed throughout the central ground tissue. A feature unique to palm stems, and one which, therefore, allows their axes to be distinguished from those of other woody monocotyledons, is the presence of stegmata, adjacent to fibrous sheaths and strands. Stegmata is small, isodiametric cells with unevenly thickened walls, which enclose a single hat-shaped or spherical silica body. They occur in linear aggregates embedding in the contiguous fibers (Weiner and Liese 1990).

Stem variation

A characteristic of palm stem anatomy is quantitative variation within and between different species, which has important biological attributes. Much inter-specific variation is related to the size of the stem, some are related to habit (notably in the scandent palms), some to habitat. Intra-specific variation both between and within single stems depends on the height of the sample above the ground, and on the changes which occur in a stem as it ages (Waterhouse and Quinn, 1978). As such, variations are of three levels as follows: (a) with size and habit or morphological (Tomlinson, 2006); (b) with height or topographical (Dransfield *et al*., 2008; Hodel, 2009); and (c) with age or chronological (Tomlinson and Quinn, 2013).

At the replanting age of a 25-year rotation, the bole length of high yielding *Tenera* palm is 9 to 13 m long with a mean volume of 1.76 m^3 (Kamarudin *et al.*, 1997). The OPT density varies with heights but typically is in the range of 200 to 600 kg m^{-3} and the average density of 370 kg m^{-3} (Lim and Gan, 2005). It is more realistic, however, to consider the stem (trunk) of the palm tree to be a composite of geometrical solids. For example, when the stem is cut into logs or bolts, as cut sections are known to wood-using industries, the merchantable portion of the stem is assumed to resemble frustum of neiloid (convex) in the region of its buttress until a point of inflection, which is located approximately 1.5 to 2 m above the ground (Figure 2.4). From there on, the tree form resembles more or less between the frustum of the paraboloid (concave) and frustum of a cone in the region to apical (Kamarudin *et al.,* 1997).

Figure 2.4: The form curve of oil palm trunk at different tree heights (Kamarudin *et al.*, 1997)

The anatomy of OPT is typical of that of the monocotyledons (McConchie, 1975; Parthasarathy and Klotz, 1976; Sudo, 1980). Hence the structure of OPT can be likened to a bunch of parallel straws (representing the vascular bundles), which are bonded together using a weak glue (representing the lignin) embedded within spongy tissues (representing the parenchyma cells). In the transverse section, there is a wide central cylinder with a very narrow cortex through where the leaf traces pass into the leaves. In the periphery of the cylinder, numerous vascular bundles with fibrous phloem sheaths are covered by the sclerotic ground tissues, which constitute the main mechanical support for the stem (Tomlinson, 1990).

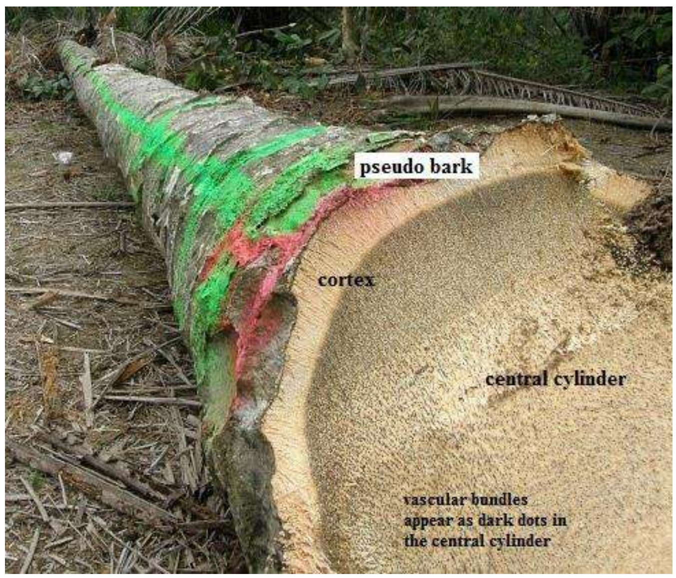


Figure 2.5: A cross-section of felled oil palm trunk showing the cortex and its central cylinder (Kamarudin *et al.*, 1997)

In a central zone, the vascular bundles are fewer and are embedded in parenchymatous ground tissues (Figure 2.5). Of the total bole volume, the number of parenchyma tissues, vascular bundles and bark (cortex) are approximately 32%, 54%, and 14%, respectively (Kamarudin *et al*., 1997). For OPT, all vascular bundles maintain their individuality and process vertically indefinitely up the stem. The vascular bundles are made of the fibrous sheath, phloem cell, xylem, and parenchyma (Killmann and Lim, 1985).

In the monocot stem, most of the space within the epidermis is filled with parenchyma cells (Dransfield *et al*., 2008). The vascular bundles are scattered throughout this area. Within a vascular bundle, note the larger xylem cells, the smaller phloem cells to the outside of the xylem, and the large intercellular passage or air space to the inside. Because there are generally two larger xylem cells and one very large intercellular passage, the vascular bundle resembles "monkey faces" (Figure 2.6) (Kamarudin *et al*., 2011).

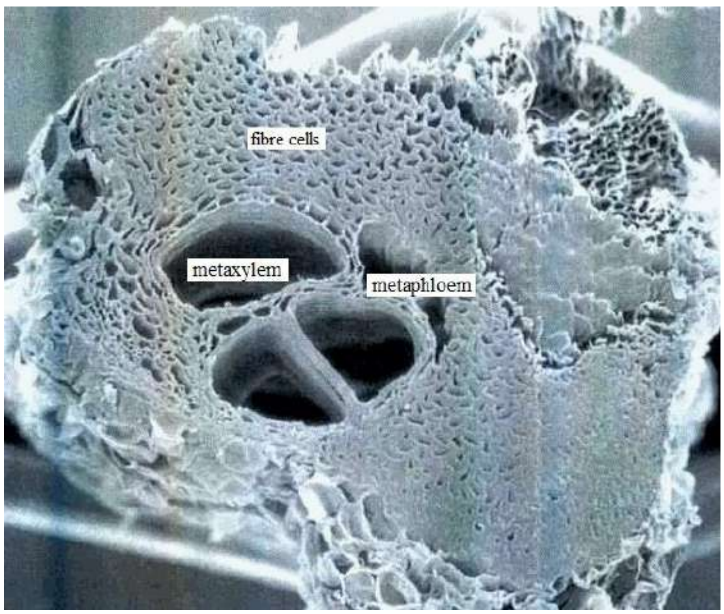


Figure 2.6: SEM Photomicrograph showing a cross-section of a vascular bundle from oil palm trunk (Kamarudin *et al.,* 2011)

The transport of water through the plant is accomplished by a system of cells arranged in long series known as sieve tubes and vessels. Other cell types, the fibres, which contribute strength and rigidity to the palm, accompany the conducting cells. The conducting tissues and the accompanying fibres are arranged in vascular bundles. In general, the vascular bundles of oil palm are distributed at random across the trunk that has no definable pith (Killlmann and Lim, 1985).

Monocotyledonous plants differ significantly from dicotyledonous trees and conifer because their cambia do not produce phloem outwardly and xylem inwardly; instead, they form collateral vascular bundles in a continuous cylinder on the inner side enclosing a pith within the stem (Sudo, 1980). In woody dicotyledons and conifers, lateral growth originates in the vascular cambium so that the stem increases in radius simultaneously with its axial growth (Philipson *et al.,* 1971).

Cell differentiation proceeds relatively quickly, with the cytoplasm dying and degenerating soon after the deposition of the secondary wall in most xylem cells (Philipson *et al*., 1971). There is no further increase in cell dimensions or wall thickness. In contrast, the monocotyledons achieve their stature without secondary thickening (Tomlinson, 1961). For the first few years of growth, the stem expands radially with little height growth and the subsequent growth occurs in the axial direction with little further radial growth due to the activity of the apical meristem. Vascular cambium is not present and most of the cells remain alive for a large part of the life of the monocotyledons (Tomlinson and Quinn, 2013).

Work by Ashari and co-workers (1991) showed that the palm age has a significant effect on the length of OPF fibers. In general, the length of OPF fibers from mature oil palm is found to be longer than those fibers from young oil palm. The average length of OPT fibres ranges from 1.23 to 1.37 mm while those fibers from OPF and EFB range from 1.03 to 1.77 mm and 0.67 to 0.84 mm, respectively (Akamatsu *et al*., 1987a, 1987b; Kamishima *et al*., 1994; MPOB, 1997).

Tissues, which are parenchymatous in nature, comprise the rest of the monocotyledon stems structure. The so-called ground tissue consists of isodiametric (Weiner and Liese, 1987) or slightly elongated and stellate parenchyma cells (Bhat, 1991) with intercellular spaces (Bhat *et al*., 1993). The cell walls of the parenchyma are usually thin, interrupted with circular simple piths. In ground parenchyma, special features cells, so-called ducts, occur. This cell possess thin unlignified walls and are either arranged solitary or in small cluster. In the longitudinal section observed bundles of raphides in the ducts. These cells are referred as to intercellular spaces in the ground parenchyma, which often modify themselves as ‘mucilage canals’ (Weiner and Liese, 1990).

A study on the parenchyma and vascular bundles of OPT using ^{13}C solid-state NMR at low field (25 MHz) indicated that the lignin structure appeared to resemble grass lignin in containing ρ-hydroxyphenyl residues but differed in containing few ferulic esters consisting of linear chains of syringyl unit links by β-aryl ether bond (Gallancher *et al.,* 1994; Sun *et al.*, 1999). The monosaccharides contained in OPT are glucose and xylose (Halimahton and Abdul Rashih, 1991). This indicates that xylans and cellulose are the predominant polysaccharides in the cell walls. Such variations will significantly affect the overall utilization of the oil palm trunk and may alter processing characteristics.

Chapter 3

Use of Wood for Sawn Lumber and Bio-composites

The tree that grows quickly in their early years, or are harvested at a young age, tend to contain a high proportion of juvenile wood (Zobel and Sprague, 1998). In general, juvenile wood is less stiff than mature wood, and the greater anisotropy tends to distort on drying. The trees harvested at short rotations are much younger and tend to be a smaller size than those from natural forests. Despite this, there is a greater need to utilize as much as possible of this resource against a background of competing, alternative as well as a requirement to preserve natural "old growth" forests. Likewise, this is a reason why the commercial exploitation of felled OPT for solid-wood and composite products is of research interest (UNEP, 2012).

Wood is a rather difficult substance to describe as its chemistry and that of its components cannot be regarded apart from its structure. Wood is not merely a chemical substance, an anatomical tissue, or a structural material. It is a combination of all three. This results from the intimate association of the chemical constituents which form its ultrastructure, and which are then combined to form higher-order systems within the walls of the cells, which ultimately compose the wood tissue. What follows is a brief account on the anatomical, microscopic and chemical features of wood pertaining to the solid-wood product and biocomposites application (Gellerstedt, 2008).

Anatomical aspects

From an anatomical point of view, wood is a perennial tissue resulting from the secondary growth in the stems, roots and branches of trees and shrubs (Pashin and Zeeuw, 1980). For sawn-lumber productions, it is the stem, or trunk, which is the main feature of interest. The trunk has three main physiological functions, to support the crown of the tree, to transport water and mineral substances between the roots and leaves, and to store reserve food (Rydholm, 1965).

Historically, the trunk is composed of three parts, the xylem or wood, the cambium, and the bark (Figure 2.7) (Rydholm, 1965). Simple inspection of wood reveals not only differences between softwoods and hardwoods but also differences within any one sample, such as sapwood, heartwood, growth rings, earlywood, latewood, and the arrangement of pores.

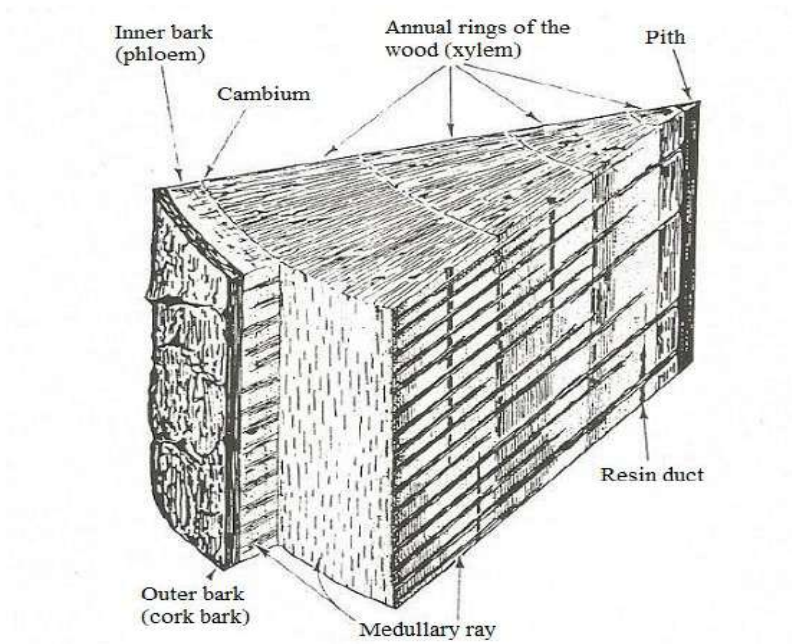


Figure 3.1: A schematic section of a four year old pine stem (Rydholm, 1965)

All these phenomena are a result of the growth and development of the wood tissue, the tissue that is constructed to meet the natural requirements of the tree and consists of strengthening, conducting and storage cells. Softwood, obtained from coniferous trees, and hardwood from deciduous trees, differ in their cell composition and cell function. The run and arrangement of cells can be recognized on the section cut in the three planes used in the anatomical characterization of wood, the cross or transverse section, the tangential section and the radial section (Table 3.1 and Figure 3.2) (Fengel and Wegner, 1984).

Table 3.1: Main functions of the various cell types found in softwoods and hardwoods

	Mechanical Function	Conducting Function	Storing Function	Secreting Function
Softwoods	Latewood tracheids	Earlywood tracheids Ray tracheids	Ray parenchyma Longitudinal parenchyma (Resin canals)	Epithelial cells
Hardwoods	Libriform fibres Fibre tracheids	Vessels Vessel tracheids	Ray parenchyma Longitudinal parenchyma (Resin canals)	Epithelial cells

(Source: Fengel and Wegner, 1984)

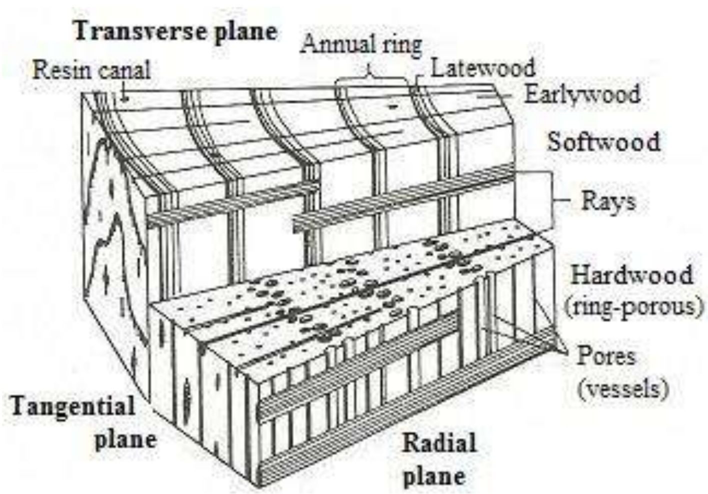


Figure 3.2: Models of a softwood and a hardwood block, showing the main cutting planes for anatomical studies, and anatomical structures visible without optical aids (Fengel and Wegner, 1984)

Softwoods show a relatively simple structures, consisting of 90 to 95% tracheids. These are long slender cells with flattened or tapered closed edges. The tracheids are arranged in radial files, with their longitudinal extension in the direction of the stem maxis. In evolving from earlywood to latewood, cell diameter becomes smaller while the cell wall becomes thicker. At the end of the growth period tracheids with small lumen develop, while at the beginning of subsequent growth periods tracheids with large lumens are usually found. This abrupt change is visible as an annual growth ring. The thick walled latewood tracheids provide strength, while the more voluminous earlywood tracheids serve to conduct water and mineral substance within the tree (Gibson and Ashby, 1997).

Hardwoods have a basic strengthening tissue composed of libriform fibres and fibre tracheids. Within this tissue conducting cells, the vessels, which often have very large lumens, are scattered. These vessels are long pipes, ranging from a few centimetres to some metres in length, and consisting of single elements with open or perforated ends. Diffuse-porous and ring-porous hardwoods are distinguished by the arrangement and diameter of their vessels elements. The dimensions of the hardwood fibres, which form the basic wood tissue, are smaller than softwood tracheids. They tend to have thicker walls and smaller lumens (Cote, 1977).

Ultrastructure of the cell wall

From the previous section, it is apparent that the structure and dimensions of the various types of cells found in wood vary considerably with species, growth condition and cell type (Neagu *et al.*, 2006). The use of electron microscopy has been extremely important in creating the current image of the fibre structure and relating it to the chemical composition of wood (Preston, 1974; Rowell, 2005).

The concentric arrangement of layers found in the cell wall is a result of difference in the chemical composition and different orientations of the various structural elements that form it. Cellulose is the main wall component, forming a framework of linear and partially crystalline aggregates called microfibrils (Samir *et al.*, 2005). The cellulose is intimately associated with hemicellulose and lignin, which form an amorphous encrusting layer on the fibrillar surfaces. The texture of the cellulosic elements becomes visible once the lignin and hemicelluloses have been removed. In this way, it has been possible to formulate the current model of cell wall construction (Figure 2.9) from observations with the electron microscope (Emerton, 1980). Between individual cells there is a thin, stiff, heavily lignified layer called the middle lamella, which serves to glue the cells together to form the wood tissue. Though single fibrils may cross the middle lamella, this layer is, in principle, free of cellulose. The transition from the middle lamella to the adjacent cell wall layers is rather indistinct, so that for the middle lamella and both adjacent primary cell walls, the term compound middle lamella may be used (Gellerstedt, 2008).

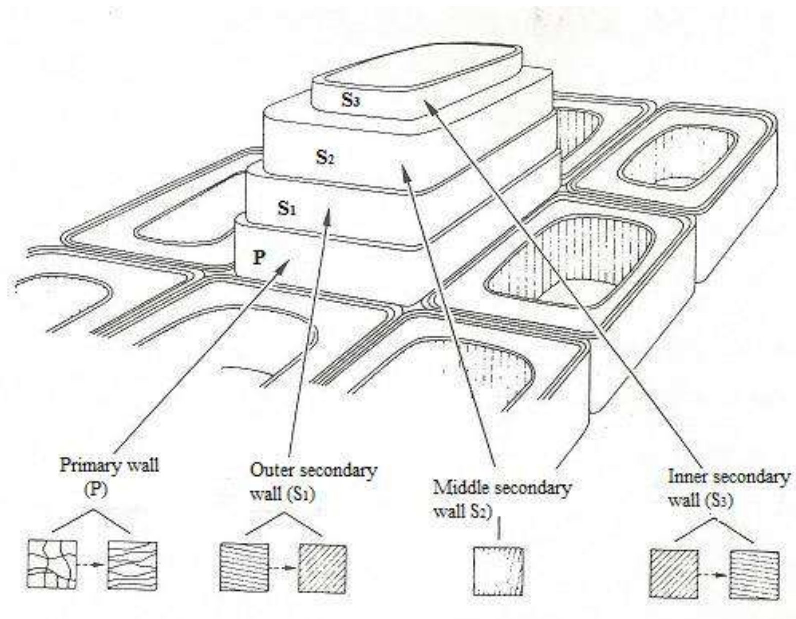


Figure 3.3: Structure of the cell wall of a typical softwood tracheid (Emerton, 1980)

In the primary wall (P), the cellulose microfibrils are arranged in thin crossing layers. As the primary wall is the first layer to be deposited during the development of the cell, this orientation allows for the expansion of the cell as it grows. The amount of cellulose present in this layer is limited (Harada, 1965). The secondary wall, formed during the maturation of the cell, is not homogeneous but is subdivided into an outer secondary wall (S_1), the main secondary wall (S_2), and the inner secondary wall (S_3). Its chemical composition is not greatly different from that of the primary wall, though there are marked dissimilarities in structure (Gibson *et al.*, 1997).

Seen from a point of view for solid-wood and biocomposites application, the structure of the cell wall may be briefly summarised as follows. The bulk of the microfibrils form a large number of coaxial lamellae in the S_2 layer, where they spiral steeply, almost parallel to the longitudinal axis of the softwood tracheid or hardwood libriform fibre. Surrounding these, the lamellae of the S_1 layer are cross-gartered and more nearly transverse in their arrangement. This serves to constrain the outward swelling of the S_2 layers when they imbibe water. External to the S_1 layer is a very thin P layer, which is not considered to be of any real technological significance, except for the fact that it contains substantial amounts of lignin. Within the S_2 layer, bordering on the lumen of the cell is a further series of lamellae, which constitute the S_3 layer. This latter is believed to be technologically unimportant (Cote, 1965).

Chemical nature

Concerning the chemical composition of wood, a distinction is generally made between the main macromolecular cell wall components, cellulose, the hemicellulose and lignin, which are present in all woods, and the minor low molecular weight components, extractives and mineral substances, which are present in different amounts in individual wood species. The proportion and chemical composition of lignin and hemicellulose differ in softwoods and hardwoods, while cellulose is a relatively uniform component of wood (Emerton, 1980). Figure 2.10 shows the general scheme for the classification of the chemical composition of wood (Fengel and Wegner, 1984).

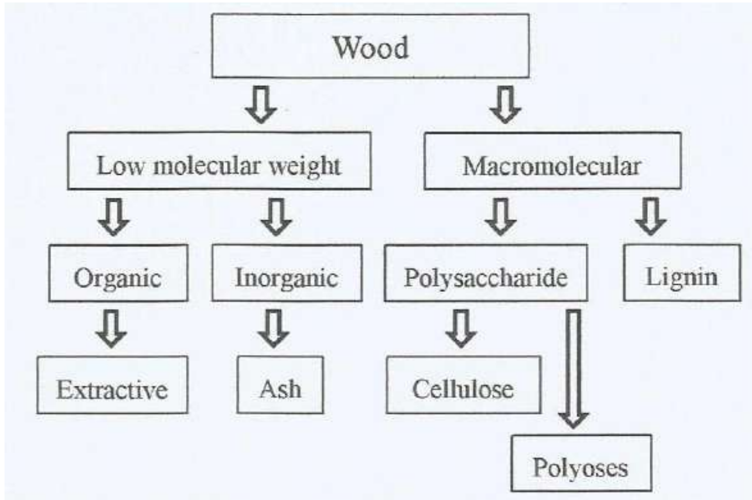


Figure 3.4: General scheme of the chemical components of wood (Fengel and Wegner, 1984)

Sawmilling Processes

Primary breakdown of saw log

A variety of saws is used to break sawlog into boards or larger dimension sawn-lumber. They are circular saws, bandsaws, framesaws and chipper canters. The first three saw types generate a saw kerf. The wood in the saw kerf is reduced to coarse sawdust. Chipper canters function differently. They chip the edges of logs, cants or flinchers to generate two parallel faces while reducing the waste material to chips, which can be sold to the fibre-based industry (Buehlmann *et al*., 2011).

Sawmills use a variety of saws to progressively cut the logs into timber of the desired dimensions. The first saw to cut log as it enters the mill is the headrig. The other saws are resawn, which further process material coming from the Headrig, and edgers, which cut and edge material. The timber is faced on all four sides and only needs crosscutting to length with circular docking saws, and where necessary, the cutting out of defects such as knots. The choice of machinery is influenced by the log resource (quality, size and volume) (Todoroki and Ronnqvist, 1999).

Bandsaw

The band-sawing process is employed at all levels of wood manufacture from primary log breakdown to cabinet shop. In primary manufacturing and in re-manufacturing, band saws are employed primarily because they waste less kerf and can be more conveniently handle large logs than can circular saws. In the woodworking shop, very narrow band saws are used because the machine can cut curves and irregular shapes that are impossible to accomplish on other tools (Maness and Donald, 1994; Chang *et al*., 2005).

A bandsaw with a log carriage is used in the breakdown of medium or large size logs (Figure 2.11) (Williston, 1988). This combination is ideal for logs of variable quality as well as those of high quality since it offers versatility in sewing patterns and a deep cut while keeping the kerf to a minimum. The logs are firmly and accurately held on the log carriage before being fed into the saw, which makes a single cut on each pass. The cut material is dropped off onto the outfeed rollers and the remainder of the log is taken back past the saw before being repositioned for another cut. With a log carriage, the log can be turned between cuts to maximize the quality and value of timber cut. The vertical knees of the log carriage, against which the log is firmly secured (dogged), can move independently to allow for log taper. Thus allow a full-length slab to be cut parallel to the cambium on any or all for sides, or the log can be cut parallel to the pith (Williston, 1989).

The teeth of wide band saws are generally swage-set; however, on narrower saws the teeth are sometimes spring-set. Spring set teeth on band saws are generally ground square on top but can be ground with alternate top bevels. The implication that spring-set teeth use less power, together with the idea that they require less care and skill in fitting, and the fact that early band saw steels were more easily spring-set than swaged all combined to keep the spring-set saw popular in many parts of the world. In Malaysia, however, where labour is relatively cheap and both power and wood are expensive, the swage-set tooth is almost universally used to achieve high production (Walker, 2006).

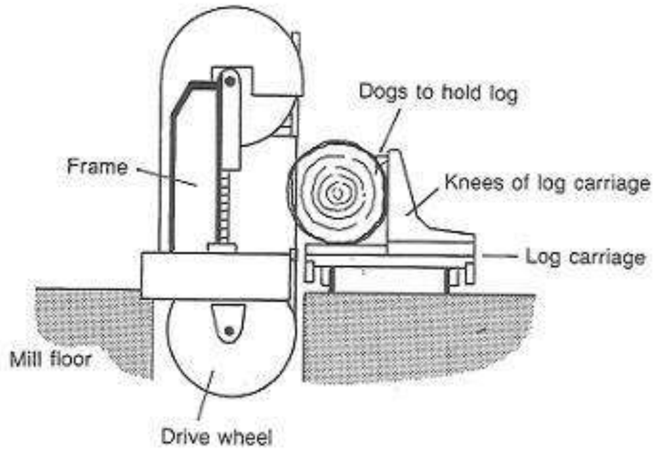


Figure 3.5: Schematic diagram of a bandsaw attached with log carriage (Williston, 1988)

Sawing of sawn lumber

Scheme of sawing patterns

The choice of selecting the sawing pattern is highly dependent on the log form and sizes. There is no single best sawing method for all logs. Initially sawing patterns are developed for the various log diameter classes bearing in mind the market for specified products and favoured product dimensions (Steele, 1984). Ferrante and co-workers (2000) considered how the use of a specific material affects the production process, and they emphasize that it is necessary to select material and process options in relation to each other.

The quality and value of sawn lumber are largely determined during the sawing process, of which the sawing pattern employed provides the basis for a profitable production of sawn lumber. In general the sawing pattern will affect the yield from the log, the grade of the sawn lumber and the sawmill productivity. When developing and modifying the equipment and concepts of sawing operations, the sawing pattern is important to consider for optimising yield (Denig, 1993).

In the case of hardwoods, sawing pattern selected is to maximize the volume of clear wood, i.e. wood essentially free from the low valued heartwood (Flann, 1978). The four basic sawing patterns adopted by most sawmills are the through-and through sawing (live-sawing), sawing around, cant- and quarter-sawn (Figure 2.12) (Erickson *et al*., 1986). Sawing around and quarter-sawing are only appropriate for large logs of more than 500 mm diameter while quarter-sawing is mainly employed by sawmills for hardwoods. In general, cant-sawing gives higher volume yields than live-sawing because in cant-sawing some of the taper in the cant can be recovered as short boards while in live-sawing this taper is lost as edgings (Hallock *et al*., 1976).

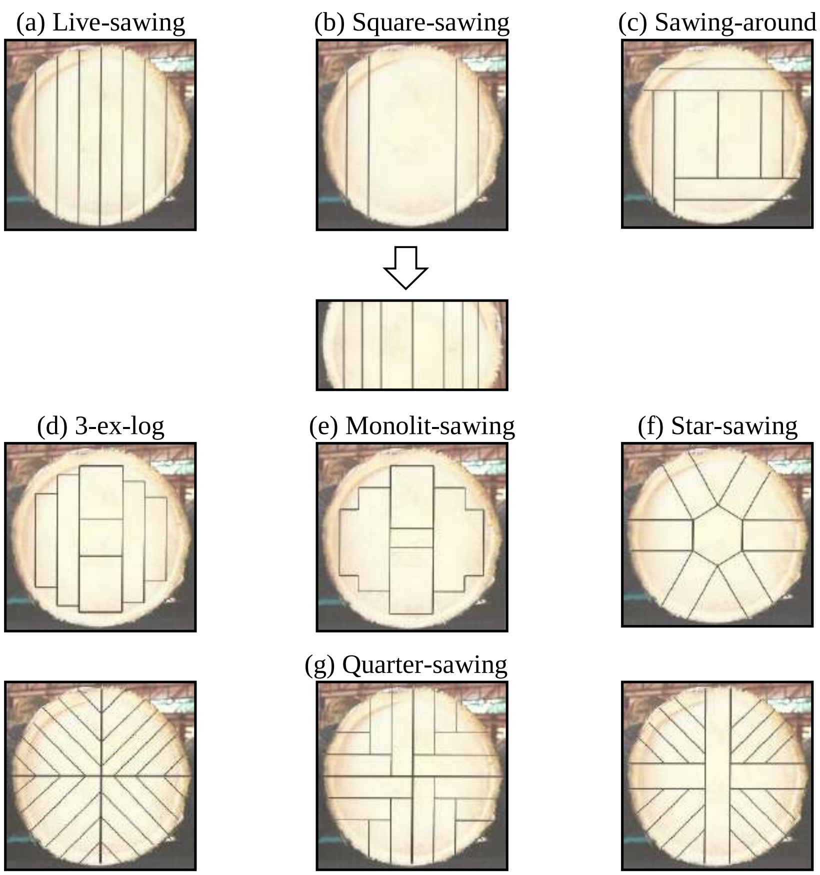


Figure 3.6: Examples of sawing pattern adopted for the primary breakdown of timber log (Erickson *et al*., 1986)

Denig and Wengert (2005) stated that live-sawing pattern (Figure 3.6a) will result in a high volume yield for small logs and produces a relatively high percentage of wood with vertical annual rings. However, the disadvantage is that middle pieces may contain a mixture of high-grade material in the outer parts together with the low-grade heart centre of the log (Anis *et al*., 2007). The square-sawing pattern (Figure 3.6b) utilizes the fact that the outer parts of the logs have higher-grade material than the centre of the log. The centerpiece is cut into boards in the primary log-breakdown process. The disadvantage is the centerpiece containing high quality material may not fully utilised in the further breakdown particularly that of large high quality hardwood logs (Erickson *et al*., 1986).

The sawing-around pattern (Figure 3.6c) starts by sawing boards from the bark towards the pith. The pattern utilizes as much high-grade material as possible from the outer parts of the logs before the centrepiece is used. The pattern requires that the logs are turned several times and results in many saw kerfs and this means volume losses. The remainder centrepiece will normally be of a very low-grade (Denig and Wengert, 2005).

Figure 3.6d describes another common way of producing planks with vertical annual ring by sawing the log with a pith catcher. The window industry employed a type of monolit-sawing to produce wooden components having vertical annual rings from timber logs (Figure 2.12e). Star-sawing (Figure 2.12f) is a way of producing sawn lumber with vertical annual rings where the sawn wood is further undergo secondary processes into knot-free and defect free wood products with vertical annual rings (Erickson *et al*., 1986). Compared to conventional sawing and post sawing processes, this method seemed to produce a volume yield in the production of knot-free boards and panels (Sandberg, 2005). Vertical annual rings are traditionally produced according to the sawing pattern called quarter-sawing (Figure 2.12g). However, this way of producing sawn lumber is inefficient because of low volume yield and it involves high production costs (Desch and Dinwoodie, 1996).

Anisotropic shrinkage and swelling of wood

Perhaps the biggest limiting factor in timber usage is their lack of dimensional stability upon drying. Wood distortions are a key quality issue for sawn lumber. Distortion is a general term to describe any deviation in a piece of timber from a plane surface. Two major processing factors that influence timber degrades are sawing pattern and kiln drying (Armstrong and Patterson, 1995). Firstly, with different sawing pattern used, the shrinkage of timber in the board width and thickness directions is different, which results in one direction of the board shrinking more than another does. Secondly, there may be corewood or transition wood on one side of the board, which shrinks more than the rest of the board. Uneven drying or over-drying may also result in more timber distortions (Denig, 1993; Armstrong and Patterson, 1995).

Drying degrades

In kiln drying, sawn lumber is dried at specified rates to minimise degrades (value loss) (Armstrong and Patterson, 1995). The dimension of a board do not change when moisture content (MC) is above the fibre saturation point (FSP) excerpt for the case of a drying problem called collapse (Jakob *et al.*, 1996). Below the FSP, however, substantial dimensional changes occur with MC changes due to the wood shrinkage (Buehlmann *et al.*, 2011). Changes in MC and MC gradient result in strain and strain-induced stresses, which may be sufficiently large to induce fracture or distortion (Salin, 1996). To minimise directional variations in use, sawn lumber needs to be dry enough to match the service environment (Steele *et al.,* 1990; Awadalla *et al.*, 2004). Thus the key philosophy behind drying is to control drying conditions so that distortion and drying induced stresses and strains are controlled at minimum levels, which in turn, will minimise degrades (Rice and Shepard, 1993).

Shrinkage in lumber dimension varies both between trees and within a tree, and therefore, such variation may be affected by the size and shape, density, the microfibril angle and the moisture content gradient when the sawn lumber is dried (Buehlmann *et al.*, 2003). All seasoning degrade is virtually due to shrinkage or to differential shrinkage within the timber. Moisture gradients (Salin, 1996) within the timber that result in differential shrinkage cause the most difficulties. Spiral grain, cross-grain and reaction wood contribute to warping, particularly juvenile wood. Drying under restrain could mitigates the problem. Alternatively, lumber degrades (Salin *et al.*, 2005) could be minimized by drying slowly but it is uneconomical.

The greater longitudinal shrinkage of compression wood compared with normal wood would cause bow and spring on drying. Compression wood is a type of reaction wood develop in trees blown over on the windward side of exposed plantations, in the lower part of trees growing on a slope and below heavy tree crown (Desch and Dinwoodie, 1996). It is characterized by its dark brown colour compared to normal wood, together with more highly developed late wood. In addition, compression wood in logs may be indicated by their shape and form (Warensjo, 2003). Since compression wood is associated with stem form correction (Mattheck and Kubler, 1995), it is reasonable to expect that a curved log is likely to contain compression wood. In fact, it is difficult to see how such a change in stem form could be accomplished without some radical change in its internal structure. For example, compression wood with thicker growth ring can cause logs to become oval in section, or exhibit pith eccentricity (Bruchert *et al.*, 2008).

Distortion on drying (as distinct from deformation under load) takes a number of forms is illustrated in Figure 2.13 (Fridley, 1993). The importance of which may be different for various applications. Diamonding (Figure 2.13a) is square cross-sections of sawn lumber with the growth rings running diagonally become diamond shaped simply because tangential shrinkage is greater than radial shrinkage. If it requires remedying the material is dressed on four sides (Steele *et al.*, 1990).

Cupping is a flatwise deviation from a straight line across the width of the board. The direction of cupping is such that the growth rings straighten out a little. In kiln drying, those boards at the top of timber stacks tend to cup in this way, the other are held flat by the weight of the lumber above. Bowing (Figure 2.13b) is the longitudinal curvature from the plane of the face in the direction of the length. Crook or spring (Figure 2.13c) is the edgewise deviation of a piece of timber from a straight line from one end to the other. Crook occurs in pithy timber where the fibres on the edge adjacent to the pith may have a large microfibril angle, spiral grain and reaction wood and so shrink more longitudinally (Danborg, 1994).

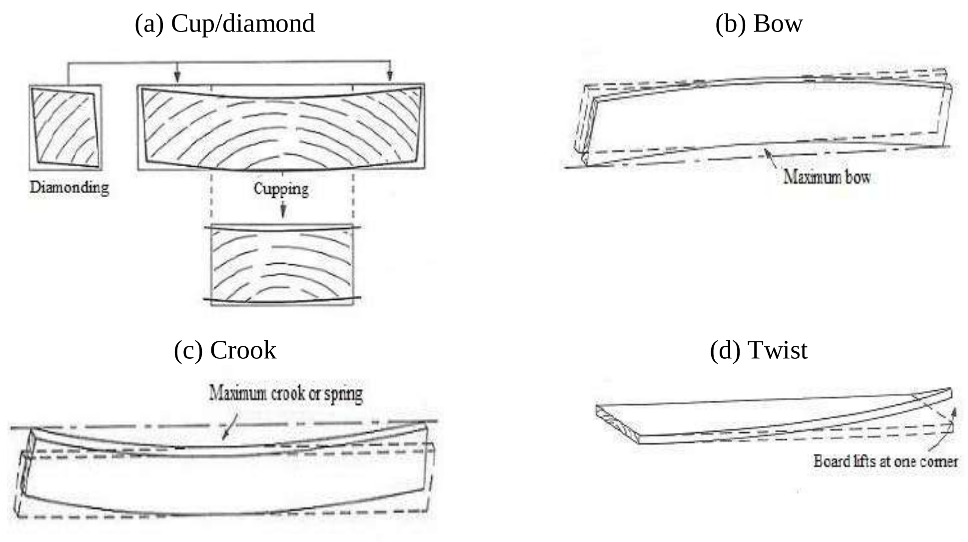


Figure 3.7: Types of drying degrade in wood showing cup, bow, crook and twist (Fridley, 1993)

Twist is a spiral distortion along the length of a piece of timber (Figure 2.13d), which is generally related to a combination of large spiral grain and the anisotropic shrinkage variation in a piece of timber (Preston, 1950; Stevens and Johnston, 1962; Kliger *et al*., 1995). It arises because the angle of the grain varies with the position of the fibres within the tree, and this happen when sawing of timber log to sawn lumber. It is also associated with cross-grain. Balodis (1972) noted that twist increased with increasing angle of spiral grain, and consequently it decreases with the distance of the board from the log pith. In general, the occurrence of twist was proportional to the ratio of grain angle to the distance from pith, and that the constant of proportionality is a function of the tangential shrinkage component of the wood (Maun, 1998).

In general wood distortion increases with decreasing of the moisture content. Dimensional instability is one of the major impediments in the processing and use of timber.

Three separate facets need to address: (a) shrinkage on drying, (b) movement in service, and (c) the responsiveness of timber to a fluctuating environment (Almeida and Hernandez, 2007).

Chapter 4

Treatments for Improved Wood Properties

The application of resin impregnation treatment to enhance the dimensional stability and strength properties of oil palm lumber (Paridah *et al*., 2006; Loh *et al*., 2010; Rudi *et al*., 2013), or any other wood material (Cai *et al*, 2007) is the use of resin adhesive, or the application of techniques, which artificially accelerated the process for improved product quality is facing a recent surge of interest. Treatments range from the application of heat to impregnation with monomers or prepolymers for *in situ* polymerization, or alteration of the chemical composition of wood by chemical reactions. Typical methods based on the process procedures can be found such as impregnation, compression, and compreg (the combination of impregnation and compression) (Ayer *et al.,* 2003).

The polymer types used in wood quality improvement are thermoplastics such as vinyl monomer and similar oligomers (Meyer, 1982), or thermosets such as phenol formaldehyde, urea formaldehyde, melamine formaldehyde and epoxy resins (Paavo and Makku, 1994). The location of the chemical added could be deposited in the cell lumen, cell wall or the combination of both in cell lumen and cell wall (Schneider, 1995).

Polymers for wood quality improvement

The study of adhesion in wood and wood-based products becomes increasingly important as work continues toward greater utilisation of our total forest resources. Consequently, there has been a rapid development of adhesive bonding as an economic and effective method for the fabrication of various components and assemblies (Schields, 1976). According to the 1980 Book of Standards (DeLollis, 1980), an adhesive is a substance capable of holding materials together by surface attachment. The holding together of two surfaces by interfacial forces, which may consist of valence forces or interlocking action, or both, called adhesion (DeLollis, 1980).

The use of adhesives offers advantages in comparison with conventional techniques such as brazing, welding, riveting and bolting. Some of the advantages are: (a) the ability to join efficiently thin sheets, or dissimilar materials, (b) the increase in design flexibility, (c) an improved stress distribution in the joint, which leads to an increase in fatigue resistance of the bonded component, and (d) a convenient and cost effective technique (Cadei *et al*., 2004).

A number of scientific disciplines that have contributed to adhesive bonding technology. On consideration of polymers in structural adhesive joint applications, Cooper and Dunnavant (1970) described the advantages of the multidisciplinary approach, of which surface physical chemistry, polymer science and mechanics are integrally involved. A pattern (Figure 2.14) that includes adhesion as well as reinforcing related areas seems to emerge when considering the interrelation of these disciplines (Adams and Wake, 1984).

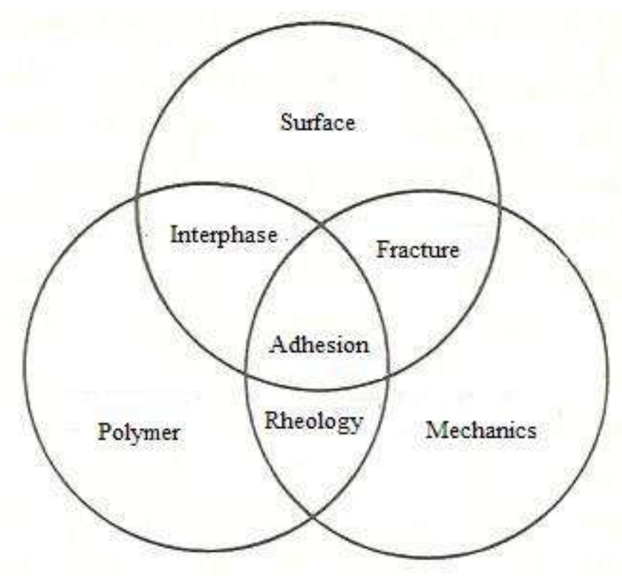


Figure 4.1: Various areas affecting and affected by the investigate interaction (Adams and Wake, 1984)

Although the interfacial properties can be critical to joint strength, it is not yet possible to predict these properties quantitatively because of dependency on the surface characteristics of the adhesive and the adherent prior to bonding, and on the surface phenomena that occur when the two surfaces bonded together (Mittal and Lee, 1997). Collett (1972) commended that modifications of polymer surfaces for adhesion orientation applications have necessitated a careful measurement of the surface region morphology (surface physics) and chemical properties of the surface layer (surface chemistry). The interaction of solid surfaces with gases or liquids leads to physical adsorption or chemisorptions of molecules or atoms on the solid surface (Marian, 1966).

The character of this adsorption depends on the surface energy of the solids and the chemical nature of the absorbents. Dispersion forces bring about physical adsorption, while chemisorption is due to the exchange of electrons between the solid and the adsorbed molecule, leading to the formation of a chemical bond, ionic or covalent. Because of this, the chemisorbed layer is usually a single molecule thick while, in physical adsorption, successive molecular layers result. These molecules adjacent to the solid surface are subject to much greater attraction forces than the subsequent layer of molecules. Usually the layers close to the solid surface are in a more orderly arrangement, which gradually disappears with the increasing distance of the subsequent layers from the solid surface (Mays and Hutchinson, 1992).

Solid surfaces can be classified as low-energy and high-energy surfaces. High-energy solid surfaces, as exemplified by most metals, various metallic oxides, diamond, quartz, glasses, and similar have surface energies ranging from 0.5 to 5 J m^{-2}, the values being higher the greater the hardness and the higher the melting point. Low-energy solid surfaces, which are characteristic of organic polymers, resins, waxes and most organic compound, have specific surface energies of less than 0.1 J m^{-2}. All pure liquid (excluding liquid metals) will wet uncontaminated high-energy solid surfaces due to surface energies greater than 0.1 J m^{-}

[2]. Low-energy solid surfaces are not wetted completely by a wide variety of pure liquids (Hayden *et al*., 1965).

Every liquid having a low specific surface energy always spreads freely on a clean, high-energy surface at ordinary temperature unless the film adsorbed by the solid converts it to a low-energy surface having a surface tension lower than that of the liquid. Liquids, which cause the formation of an adsorbed and orientated layer on a solid surface resulting in a low-energy surface (even lower than that of the spreading liquid) called autophobic (Pimentel and Spratley, 1969).

The contact angle of a liquid with a solid surface is a convenient measure of wettability, which is an indicator of the affinity of a liquid for a solid. Contact angle measurements are made in various ways, but all essentially refer to the equilibrium of a drop of a liquid resting on a plane solid surface under the action of three surface tensions are as follows: (a) at the interface of the liquid phase and vapour phase, γ_L; (b) at the interface of the solid phase and the liquid phase, γ_{LS}; and (c) at the interface of the solid phase and vapour phase, γ_S (Jastrzebski, 1977).

The mechanisms of adhesion may include mechanical interlocking, diffusion theory, electronic theory, adsorption theory, chemical reaction, interdiffusion, Van der Waal's forces, and dipole-dipole attraction. However, none of these theories can fit every situation, and frequently several of them appear to play a role in bonding. It is suggested that acid-base interactions at the adhesive-adherend interface could play very important role in adhesion. Evidently, the practice of adhesion science reveals that it is not a simple phenomenon comprehensible with a single model. The physical reality tends to suggest that several models operate at the same time (Kinloch, 1983).

Chemical bonds, once regarded as unnecessary to explain joint strength or adhesive action, are now seen to be quite common and for ionic bonds to be closely linked with the electrostatic theory. Diffusion as the mechanism of auto-adhesion of elastomeric polymers and adsorption admitted to explain the wetting of surfaces by liquids, are essential preconditions for adhesive action. Adsorption or the sense of orientated molecules on fixed sites is applied for many cases of polymeric adhesives on high-energy solids (Shi and Gardner, 2001).

Adhesive bonding has many advantages to offer the building industry. No other method of attachment is satisfactory for so many applications. It would be absurd to consider nailing a ceramic wall tile into position or to use plywood paneling which has its wood plies stapled together. Even sandpaper depends on an adhesive to hold the grit to its paper backing (Mittal, 1975). When all the applications of adhesives are taken into account, adhesive bonding must be considered as the most widely used method of holding various materials together. The important of the surface polarity and other surface characteristics for polymer adhesion has been considerably discussed in recent years (Lee, 1984).

Properties of gum rosin

The rosin (non-volatile solid form of resin) is produced by one of three routes: (a) gum rosin is obtained by tapping living pine trees, and then distillation the exudate (oleoresin) to produce rosin and turpentine, (b) wood rosin is produced by solvent extracting aged pine stumps, and (c) tall oil rosin, which is the useful by-product of the kraft pulping process. The production of rosin is more than 1 million tonnes per year (Liu and Urban, 2010). Over the years, the rosin is used in a wide range of applications such as in the manufacture of adhesives, paper sizing agents and printing inks (Smith *et al*., 2010; Yao and Zheng, 2000; Alexander and Shakesheff, 2006).

Gum rosin consists primarily of abietic- and pimaric-type resin acids with a suitable hydrophobic character and affinity for lignocellulosics (Satturwar *et al*., 2005), is given in Figure 2.15. Different chemical mechanisms between copper, rosin and wood constituents have also been investigated (Voulgaridis, 1993). For example, the copper-rosin soaps were extremely efficient towards both fungi (unsterile soil bed test) and termites (field test) (Fizzi, 1993). In another study, the decay resistance of wood seemed to improve due to the decreased in moisture absorbing tendency when subjected to a rosin sizing agent (Li *et al.*, 2011), and are of primary interest in this work.

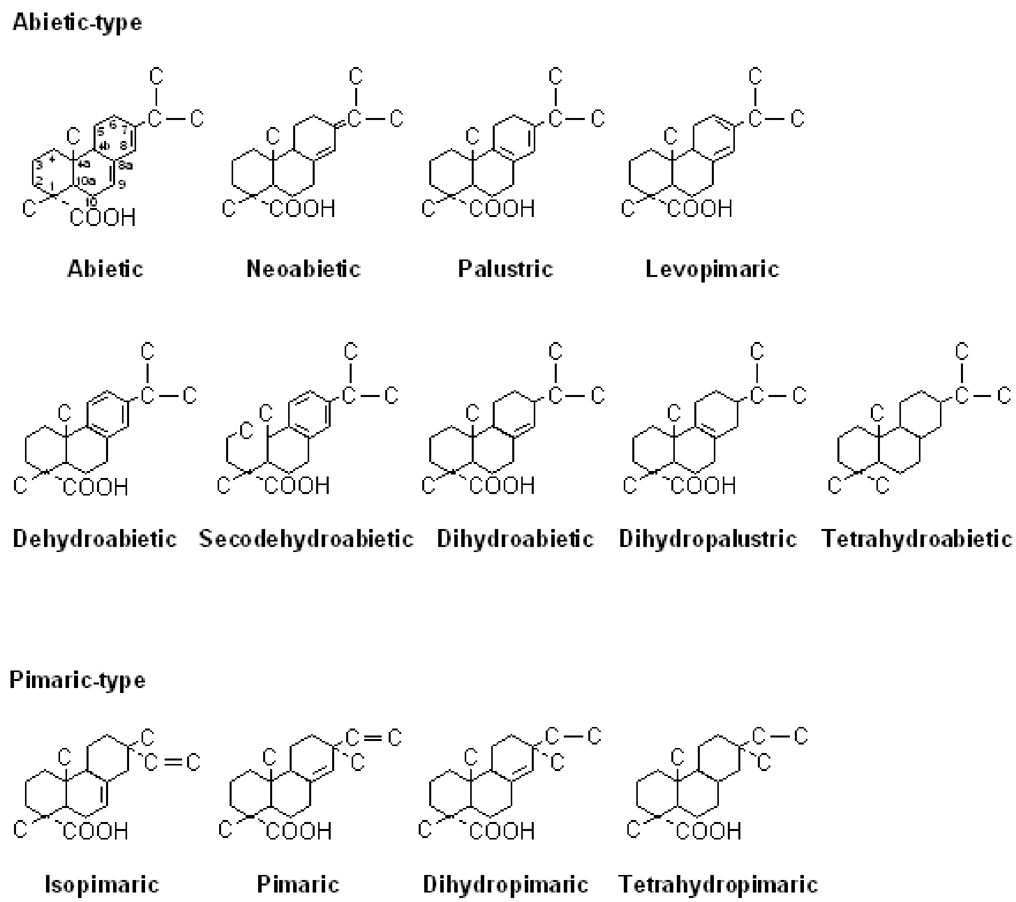


Figure 4.2: Chemical compositions of gum rosin

Densification of wood materials

Different methods have been developed for the production of densified timber products (Rowell and Konkel, 1987). Densification can increase the bulk density of biomass from an initial density of 40 to 200 kg m^{-3} to a final compact density of 600 to 1,200 kg m^{-3} (Holley, 1983; Mani *et al.,* 2003). Procedures generally involve transverse compression of timber under conditions where the wood is sufficiently plasticized. (Obernberger and Thek, 2004; Adapa *et al.,* 2007).

Densified wood, a part of improved wood or modified wood has been done to two main approaches; (a) either by filling the lumens and cell walls with suitable substance, often a resin, or (b) lowering the porosity by filling the void with wood substance through compression process (Deka and Saika, 2000). Sometimes the two methods are combined (c) resulting in products that are sometimes called compregnated wood (Seborg *et al.*, 1945).

Compreg is the product name given to compressed wood products that are manufactures by impregnating solid wood or veneer with a thermosetting resin. The resin used is a fibre penetrating phenol formaldehyde resin. Resin treated timber is compressed under platen temperature of 150 °C and platen pressure of 6.5 MPa, with the deformation occurring before the thermosetting resin cures. Compressed timber products can be produced with specific gravities of 1.20 to 1.35 (Stamm, 1964). Ironically, structural-size compressed timber is generally difficult to manufacture using compreg. This is mainly due to the difficulties in achieving full resin penetration into the timber and due to the curing of the thermosetting resin adjacent to the high temperature platen, before full densification has occurred. For this reason, compreg is mainly used in the manufacture of veneer products (Dogu *et al.,* 2010).

Two other compressed timber products are *Lignostone* and *Staypak*. Both products are made by compressing untreated solid wood (without resin added) with hot platen at temperature ranging from 160 to 180 °C and pressure between 10 to 18 MPa. *Lignostone* was produced by first applying pressure in one direction (radial) and followed the application of pre-compression pressure in two directions (radial and tangential). In this state, the wood was heat treated before the pressure is released. The described process resulted in an increase in density from 650 to 1450 kg m^{-3} for wood. For the *Staypak* products, wood was compressed with side restrains because there is the tendency for the wood to spread perpendicular to grain when the thickness was 12 mm or more (Galperin *et al.,* 1995).

The strength properties of *Staypak* products are improved when compared to standard timber, as reported by Stamm (1964). Structural and veneer *staypak* timber products can be manufactured using a process which is less material and process intensive than the compreg process. Manufacturing issues with *staypak* products from plantation pine are high concentration of water-insoluble extractives, which is present in pines, will retard lignin flow and impede timber compression.

Tabarsa and Chui (1997) have completed research on timber processing methods similar to Staypak which investigated the concurrent effects of compression and platen temperature on the properties of white spruce timber. The timber with an initial moisture content of 15% was processed using platen temperatures of 20, 100, 150 and 200 °C and densification levels of 12, 16, 24 and 32% to produce test specimens of 210 mm long, 20 mm wide and 12 mm thick. The compression was applied to reach densification level within one minute and was maintained for a further four minutes.

Densification was primarily made to increase the abrasion resistance and the mechanical properties. In most methods used for densification of wood, heat and steam were involved. There are also often been pressure in only one direction at a time. One of the main problems associated with most of the types of densified wood (except to those with high resin content) is the lack of dimensional stability. When soaked in water or exposed to high relative humidity, compressed products tend to exhibit irreversible swelling or springback (Saito, 1973). This can be a serious problem when densified wood is used in high humidity environment. Thus, it is important to determine the pressing condition under which the recovery from compression for untreated compressed wood is minimized.

Wood densification by thermal transverse compression has attracted many researchers as a process to improve the strength and surface properties of low-density wood species (Hillis, 1984). For instance, press drying aims to rapidly season green timber between heated platens and is generally a constant pressure operation (Onishi *et al.,* 1984; Schmidt, 1967). The level of pressure applied to the timber has varied in research and industry from low level to ensure contact between the timber piece and the platens, to higher levels causing low levels of timber densification. Press drying procedures are generally designed to minimized thickness loss of the timber piece.

In research done by Simpson and co-workers (1988), green loblolly pine of 50 mm thick and 100 mm wide was press dried in 90 minutes by using platen temperature of 175 °C and platen pressure of 175 and 345 kPa. The resulting timber was reported as being successfully seasoned and free of checking, cell collapse and excessive thickness loss. There was minimum difference in the timber that was restrained in the press after cooling or removed from the press and was unstrained during cooling. Timber samples dried at 175 kPa produced a statistically significant reduction in warping, a downgrade of 4% compared to that of kiln timber that varied from 18% to 30%. The specific gravity, strength and stiffness increased by 7.0%, 12.9% and 19.0% for timber pressed at 175 kPa.

Thermomechanical densification has fundamental differences in aims and objectives compared to compreg, staypak and press drying manufacturing methods, which typically apply to discrete parts of the processing procedure and in the case of compreg, are resource intensive to produce. This method uses high temperature platens to rapidly season and densify timber. Pressure is applied to densify the timber under conditions of maximum plasticity and over a discrete time interval. Restraint of the timber piece is required after the timber has been densified, during the conditioning process. This is due to the thermo-plastic nature of the lignin in the timber which endeavour to recover to its original form after the application of stress and whilst still at high temperature (Inoue *et al*., 1996).

Chemical treatments

The permeability to water of wood cell wall material is of importance in studies of the treatment of wood with aqueous solutions, such as water-borne preservatives, and in investigation of the movement of water in the living tree. Bailey and Preston (1970) suggested that aqueous preservative solutions might flow through cell walls by way of cell wall capillaries. Although axial flow of water in the stem of the living tress occurs through cell cavities and pits, some lateral flow may occur through cell walls.

Solid wood in its many form and adaptations has been the most versatile material for buildings, construction, or furniture because of superior material properties, e.g. pleasing optical appearance, favourable mass to strength ratio, low thermal conductance, biodegradability, and last, but not least, due to its neutral carbon dioxide balance. There are, however, solid wood properties that are often perceived as negative by the end-users, such as dimensional stability with changing moisture content, low natural durability, expressed photo-yellowing, or unsatisfying mechanical properties (Johannesson *et al*., 2004).

A promising way to improve wood properties is though controlled chemical modification. A number of chemical substances have been tested (Masuda, 1996), and some have shown improvement in the dimensional stability and/or decay resistance of wood (Rowell, 1996; Militz *et al*., 1997; Salamah *et al*., 1988; Yalinkilic *et al*., 1999). However, chemical modification treatments have shown insignificant and slightly negative effects on the mechanical properties of wood (Larsson and Simonson, 1994; Rowell, 1996; Ramsden *et al*., 1997).

Early treatment used to dimensionally stabilize wood include tars, creosote, resins and salt, which coated of filled the cell lumen (Meyer, 1982). Since then, considerable research on wood treatments has been carried out with numerous introduction of new treatments on wood stabilization (Barclay, 1981; Grattan, 1980; Kazi *et al*., 1997; Sergey *et al.,* 2001). Examples include polyethylene glycol (PEG), heat-cured phenol formaldehyde resins, reacting with acetic anhydride and cross-linking with formaldehyde or multifunctional isocyanides.

Thermosetting synthetic resin such as epoxy, polyester and methyl acrylate are chemically or radiation curing synthetic polymers. This category of synthetic resins has been commercially applied in the manufacture of fibre-plastic composites (Startsev *et al.,* 1999; Gindl *et al*., 2003) and is known to impart strength and improve other properties of undergraded wood. Research to date indicates that wood treated with these compounds have reduced checking, warping and twisting compared to matched untreated controls (Nicholas, 1972; Schniewind *et al.,* 1982; Watanabe *et al*., 1998; Bergander and Salmen, 2002).

Kutnar and co-workers (2008) studied mechanical properties of viscoelastic thermal compression (VTC) made of low-density hybrid poplar (*Populus deltoids* x *Populus trichocarpa*). The results showed that the bending properties of VTC wood were significantly enhanced due to increased density. A study on the performance of a wooden block shear wall utilizing compressed wood as a connecting element in place of the traditional connecter (Hassel *et al*., 2008). They reported that the compressed connectors recovered its radial dimension partially and filled the gaps with the adjacent blocks after absorbing moisture from air. Kitamori and co-workers (2010) investigated strengthened properties of compressed *Sugi* as connecting elements in joints. The results showed that the shear modulus and strength increased almost proportionally to density.

Melamine-formaldehyde (MF) resins have potential to improve properties of solid wood. Impregnation of solid wood with water-soluble MF resins has led to a significant improvement of surface hardness and MOE (Miroy *et al*., 1995; Deka and Saikia, 2000). Furthermore, resistance to weathering has increased and colour changes due to ultra-violet (UV) irradiation diminished with increasing concentration of MF-resin in wood (Inoue *et al.,* 1993).

The use of low molecular-weight phenol formaldehyde resin (LMWPF) has been reported by many researchers as additional treatment to enhance the properties, particularly the strength and dimensional stability of the lignocellulosic materials. Among the products studied were oil palm veneer for plywood (Loh *et al.*, 2010), bamboo plywood (Anwar *et al.,* 2011), particleboard (Kajita and Imamura, 1991), wood lumber (Furano *et al.,* 2004; Abdullah, 2010), multi-layered strand board (Paridah *et al.*, 2006) and laminated veneer lumber (Sulaiman *et al*., 2009).

The LMWPF had been used to treat softwood lumber against fungi attacks (Evans, 2003), biodegradation (Ryu *et al.,* 1991) with improved dimensional stability and strength of the wood (Imamura *et al.,* 1998) and reconstituted boards (Kajita and Imamura, 1991; Paridah *et al*., 2006). Yazaki (1996) stated that the bond strength of phenol formaldehyde (PF) resin is high and its deterioration at elevated temperature in the presence of moisture is better than urea formaldehyde (UF) and melamine-urea formaldehyde (MUF) resins. In fact, PF resin is known of its high strength, resistance to moisture, good dimensional stability and low cost (Koch *et al*., 1987; Pizzi, 1994).

The quality of OPT lumber can be improved by filling the cell walls of parenchyma tissues with PF resin until the cell wall is swollen (Kamarudin *et al*., 2007). Dimensional stability is achieved due to bulking of cell wall and cross-liking between the cell wall polymeric components (Rowell, 2005), leading to a reduction of equilibrium moisture content (EMC) at a given relative humidity (RH). Hence, a reduction in the cell wall moisture content will result in an increase in MOE and in strength (Dinwoodie, 2000).

Abdul Khalil and co-workers (2008) indicated that the mechanical properties of sawn lumber of 100 cm (long) by 20 cm (wide) by 10 cm (thick) from oil palm trunk increased with an increase of resin loading from 5% to 25% by using modified phenol formaldehyde resin, but the strength tended to decrease with an increase of resin content above 25%.

Edi Suhaimi and co-workers (2008) stated that oil palm lumber (40 mm in radial by 100 mm in tangential by 100 mm in longitudinal) impregnated with medium molecular weight phenol formaldehyde (MMWPF) resin to act as bulking agent for an hour and compressed under hot pressing of 45% compaction tended to increase the density from 0.37 to 0.98 g cm^{-3}. In addition to strength properties, the dimensional stability, durability and machine ability of resulting treated lumber has increased significantly.

Mohd Fahmi and co-workers (2008) concluded that the swelling of OPT lumber was higher in solvent with low molecular weight compared to that solvent with higher molecular weight. The rate of swelling is higher in the radial direction as compared to tangential swelling while the axial swelling is considered negligible when subjected to organic solvent such as n-hexane, cyclohexane, acetonitrile and acetone.

Vacuum Infusion Process

Vacuum infusion (VI) technique is renowned and established since long. However, process development has until recent years mostly been based on trial and error. Hence, the behaviour of the process is not fully understood and the modelling is so far not sufficient. It is obvious that an increase in part size and the corresponding increase in material value stresses the risk of severe economic loses in the case of an unsuccessful charge. Moreover, the process is sensitive to leakage in the flexible membrane and a good surface finish is only available on one side of the part. Complex geometries such as sharp edges and thickness variations can disturbed the flow of resin (Bickerton *et al.,* 2000).

The VI is known under different acronyms. They are: Vacuum assisted resin transfer moulding (VARTM), Vacuum bag resin transfer moulding (VBRTM), Vacuum assisted resin injection process (VARI), Resin injection under flexible tooling (RIFT) and Seemann composite resin infusion moulding process (SCRIMP™). All involved the same technology based on the impregnation of a dry reinforcement by liquid thermoset resin driven under vacuum pressure. Some of the technology are patented to cover different elements of the process and its generic names (Rudd *et al.,* 1997).

The VI is increasing popular in the transportation, marine, manufacture of large composite parts, in which thick, single skin laminates and sandwich structures are being produced using this method (Brouwer *et al*., 2003). Components are made of glass fibres and polyester resin. Weidje and co-workers (2002) mentioned that the VI process is also being used for the manufacture of carbon fibre-epoxy component dedicated to aeronautic and aerospace sectors. In VI process, the infusion of resin is carried out under imposed pressure or flow rate. Since the cavity thickness is constant, the permeability of the substrate remains constant during the infusion (Hoebergen, 2001).

Material Strength of Oil Palm Trunk for Sawn Lumber

The commercial exploitation of oil palm for a variety of products depends on a number of factors. These include a long-term security of sustainable supply, the economic system for handling them and a reliable design of processing and manufacturing equipment to cater for their physical forms and sizes. Adding to these requirements, sawn timber to be used should possess some desirable mechanical properties such as stiffness, strength, toughness and creep (Ward and Hadley, 1993), which generally influencing both the processing behaviour and the product quality (Kellogg and Wangaard, 1969; Ando and Onda, 1999).

General information concerning the mechanical properties of sawntimber can be obtained from a bending test, which expresses fracture event in terms of equations containing measurable parameters, such as stress, strain and linear dimensions. Stiffness or the resistance to deformation is measured by moduli of elasticity, such as Young's modulus, bulk modulus and modulus of rigidity. Strength, computed as ultimate stress (the stress at the highest applied force) demonstrates the ability of sawntimber to withstand bending to the point of rupture. Toughness represents the work required to fracture a material while creep is a measurement of time-dependent deformation under constant load and is more prominent for isotropic and amorphous polymers (Conners and Medvecz, 1992). On a microstructure scale, it is possible to measure the strength of linear crystalline fibres using the valence-force type of calculation, which is based on the knowledge of the bond angles and the respective force constant, bond lengths and the unit cell dimensions. However, native fibres seldom achieve the theoretical strength although freshly drawn glass fibre and certain whisker crystal do appear to exhibit tensile strengths approaching the theoretical limit (Andrew, 1968).

In general, macroscopic deformation of cellulosic fibres may involve several microscopic deformation than include valence bond length and angle deformation, secondary bond deformation, reorientation of macromolecules in amorphous regions, reorientation of crystalline regions and configurationally entropy effects. With such complicated mechanisms of fibre deformation, the theoretical estimates of fibre strength tend to be of doubtful significance compared to that of the measured moduli using appropriate test methods (Djordjevic *et al*., 2007). Compared to theoretical estimates of fibre strength, the modulus (or compliance) which is generally a simpler property to model can be easily related to the binding energies within the molecular structures such as the degree of orientation and crystallinity along the direction of the fibre axis (Fengel and Stoll, 1973). Therefore, modulus, which is a true reflection of fibre strength, is often the first mechanical property to be determine when 'new' cellulosic fibres are introduced.

Tensile modulus is widely used to measure the macroscopic stretching which involve either stretching a fibre sample and monitoring the load, or loading it while monitoring the extension of a fibre at low strain rates. The apparatus used for simple extension tests are usually commercial tensile testing machines, for example an Instron, where the fibre is stretched at a constant rate of elongation. These employ a crosshead moved by lead screws driven by a powerful motor, capable of a range of speed while loads are measured using a hard load cell connected to appropriate amplifiers (Tucker and Liang, 1999). Some form of extensiometer measures extension or strain gauge attached to the specimen or from the crosshead displacement if the specimen used is particularly delicate. For uniaxial tensile load, it is generally assumed that the load is shared uniformly across the fibre and the sample maintains a constant cross-section over the measured region, at least (Djordjevic *et al*., 2007).

There are two moduli, which can be defined from the simple uniaxial tension experiment: the secant modulus and the tangent modulus. For non-linear elastic material, both moduli depend on the strain and extension rate at which they are measured. The tangent modulus is the slope of the tangent to the stress-strain curve at the given strain and extension rate, while the secant modulus is the slope of the line from the origin to the stress-strain curve at the given strain (Bodig and Jayne, 1982).

Chapter 5

Procedure of Impregnation of Oil Palm Lumber with Gum Rosin

Thirty oil palm trunks (OPT) were provided by MPOB (Malaysian Palm Oil Board). The oil palm trees of high yielding *tenera* variety (a hybrid between those of *dura* and *pisifera*) were collected during the replanting operations at Sungei Kahang Estate in Johor. Prior to felling, only those oil palm trees whose bole is straight and free from visible defects were selected. All sample trees were classified under the same diameter class between 45 to 52 cm (measured at one meter above the ground) and the bole length ranged from 11 to 13 m long. After measuring the length (Figure 5.1), the palm trunk was then cross cutting to three samples billets, each of 4 m long.

Figure 5.1: Length of felled oil palm trunk prior to cross cutting into billets

The billets were labelled with codes indicating the palm number and its position within the tree height. The billets were loaded onto a lorry and transported to MPOB/UKM Research Station, which is located in Pekan Bangi Lama, Selangor for the preparation of oil palm lumber samples. The breakdown of OPT billet into lumber scantlings was done using a 9-foot band headrig with a log carriage (Figure 5.2). After securing on the log carriage with dog spikes, the OPT billet was fed into the saw by a powered winch. The saw made a single cut on each pass.

Figure 5.2: Primary breakdown of oil palm trunk into sawn lumber using a 9-foot band headrig with log carriage

The cut material collected from out-feed rollers and the remainder of the log had taken back past the saw and repositioned it to another cut. With a log carriage, the OPT billet was turned between cuts to maximize the quality and the value of log cut. The vertical knees of the log carriage, against which the log was dogged, can move independently to allow for log taper. This allows the sawing of OPT billet to its full-length slab, cut parallel to the pith. Feed speed was 1.2 m s^{-1}, and the return speed was twice as fast.

Physical Properties of Oil Palm Trunk

Preparation of test samples

Five OPT were selected to determine the moisture content and basic density in pith to periphery zone with tree heights, is illustrated in Figure 5.3.

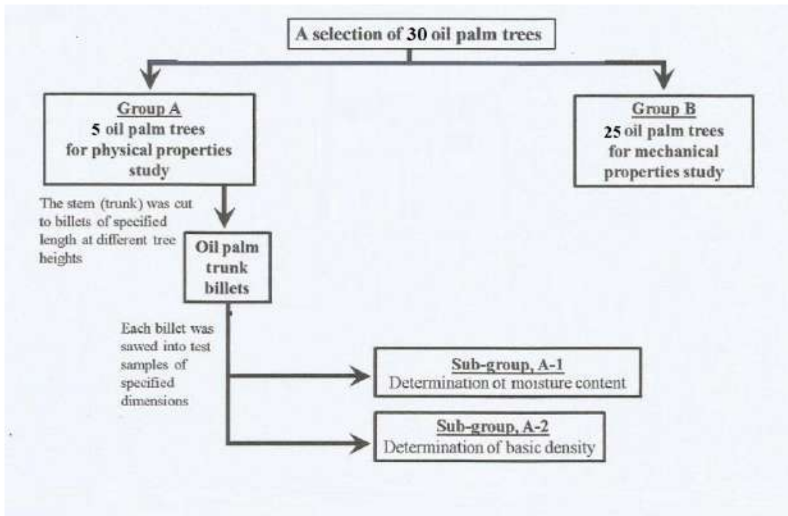


Figure 5.3: Preparation of oil palm lumber for physical properties study

The OPT in group A was divided into two subgroups, namely (a) Subgroup A-1, determination of moisture content, and (c) Subgroup A-2, determination of basic density. After sawing, the test samples were then labelled by using a permanent marker pen with codes according to palm number, height level, position and the location of test sample taken across the diameter. Test samples were marked using the following codes: Inner zone (pith), test sample taken in pith to 50 mm towards periphery; Middle zone (intermediate), test sample taken at 50 mm to 100 mm from the pith towards periphery; Outer zone (periphery), test sample at 100 mm to 150 mm from the pith towards east. Procedures for sampling to determine the physical and mechanical properties were done in accordance with International Standards Organisation, ISO 3129-1975 (1975).

Determination of moisture contents

The OPT is a porous material containing numerous elements such as air, water, ground parenchymatous tissues and cellulosic materials. As a result, the weight of a piece of sawn lumber cut from the trunk is not constant. The sawn OPL tends to lose or gain moisture depending on the environmental conditions to which it is exposed. Moreover, the volume of a piece of OPL is not constant. In general, the OPL will shrink and swell as it loses and gains moisture (Cown *et al.,* 1996). It is therefore essential to know how much water contains in a piece of sawn lumber before attempting to determine any other property.

Moisture content (MC) was determined in accordance with ISO 3130-1975 (1975) procedures. After sawing, the test samples (in subgroup A-1) having a square cross-section of 20 mm and the length, along the vascular bundles, of 25 ± 5 mm were stored in a plastic bag. This was carried out in order to ensure its moisture content will remain unchanged during storage. Test samples were weighed individually to the nearest 0.01 g to obtain the green weight. After weighing, the samples were dried in an electric oven (Memmert, UFE 600) at 103 ± 2 °C until constant in order to obtain the dry weight to the nearest 0.01 g. The samples were further reweighed at equal hourly intervals and the weights recorded until no weight loss was detectible.

At the end of the final period, test samples were cooled in a dessicator over silica gel. After cooling, the sample was weighed rapidly enough in order to avoid an increase in moisture content by more than 1%. The difference in the two values between the initial and constant weights is assumed to be due to loss of water by evaporation during drying. The moisture content, MC_{od} of each test sample, as a percentage by mass were calculated as follows (ISO 3130-1975):

$$MC_{od}\ (\%) = \frac{(W_g - W_{od})}{W_{od}} \times 100 \qquad \text{(Equation 5.1)}$$

where MC_{od} is the moisture content on an oven-dry basis in percentage, W_g is the mass, in grams, of the test sample before drying, and W_{od} is the mass, in grams, of the test sample after drying.

Determination of basic density

The density of OPT is measured once its MC has been defined. In physics, the density of a material is described as the mass per unit volume (kg m^{-3}). The situation is quite complicated because changes in moisture will affect both the mass and volume (Olesen, 1971). The term 'basic' emphasizes that both parameters measured, the oven-dry mass and the swollen volume, have constant and reproducible values. Hence basic density would be the most useful descriptor of OPT density.

The BD was obtained using green volume and oven-dry mass of each test sample in accordance with ISO 3131-1975 procedures. Test samples (in subgroup A-2) were prepared in the form of a square cross-section of side 20 mm and length along with the vascular bundles of 25 ± 5 mm. In order to ensure the moisture content remains unchanged, the test samples were stored in a plastic bag after sawing.

The weight of test samples was measured with a digital balance to the nearest 0.01g while its volume to the nearest 0.01 ml was determined by the water immersion procedure before drying. The samples were coated with molten wax and immersed in water. The weight and the latest water level of the volumetric cylinder were recorded. After soaking, the specimens were oven-dried in an electric oven at 103 ± 2°C until constant weight to obtain the dry weight to the nearest 0.01 g and cooled in a desiccator over silica gel. After cooling in a desiccator over silica gel, the test sample was weighed rapidly enough in order to avoid an increase in moisture content by more than 1%.

The basic density, BD of each test sample, as a ratio of mass per unit volume was calculated from the relationship as follows (ISO 3131-1975):

$$\text{BD (kg m}^{-3}) = \frac{W_{od}}{V_g} \qquad \text{(Equation 5.2)}$$

where BD is the basic density in kg m^{-3}, W_{od} is the oven dried mass of test samples in kg, V_g is the volume of green test specimen in m^3.

Mechanical Properties of Oil Palm Lumber

Preparation of oil palm lumber samples

A total of 25 OPT were selected to obtain lumber scantlings, is given in Figure 5.4. Oil palm billets of 80-cm long were cut at the 2-m, 4-m and 6-m height levels. This technique should sample the OPT, taken as a whole. From group B, the oil palm billets were divided into two subgroups as follows: (a) Subgroup B-1, determination of the bending strength of matched OPL samples dried at 10 ± 2% moisture content, and (c) Subgroup B-2, determination of the bending strength of matched dry OPL samples subjected to gum rosin and densification treatments.

The billets of each subgroup B-1 and B-2 were then sawed to produce lumber scantlings with nominal dimension of 100 mm wide in radial by 100 mm thick in tangential and 800 mm long in longitudinal directions. After sawing, the lumber scantlings were then labelled by using a permanent marker pen with codes indicating the position and the location within the bole diameter with tree heights.

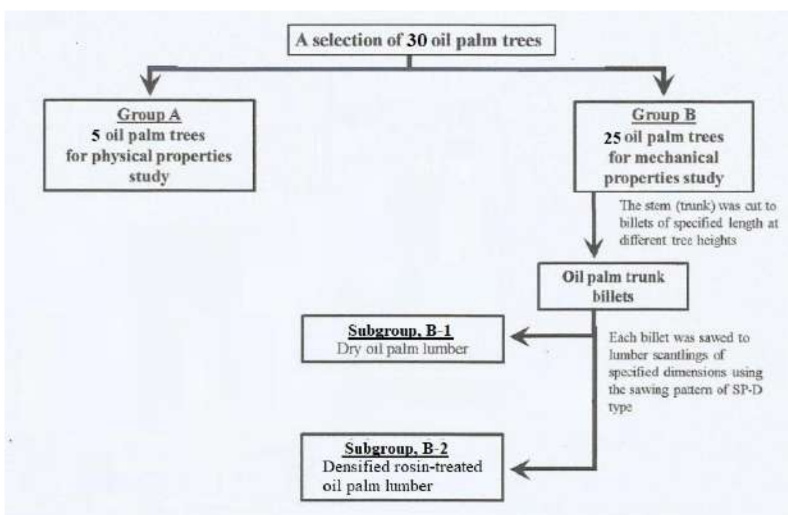


Figure 5.4: Preparation of oil palm lumber for mechanical properties study

Treatments of oil palm lumber

Dry sawn lumber

For subgroup B-1, the OPL samples were left to dry in an electric oven at 60 ± 2 °C and weighed daily until the MC reached 10 ± 2%. After drying, the OPL samples were trimmed and dressed to size in the form of a square cross-section of side 20 ± 1 mm and length along the vascular bundles of 300 ± 1 mm using a circular bench saw. The OPL samples were stored in a plastic bag in order to avoid moisture changes during storage. The OPL dimensions and its MC were recorded prior to bending strength tests.

Densified gum rosin-treated lumber

From subgroup B-2, the OPL samples were left to dry in an electric oven at 60 ± 2 °C and weighed daily until the moisture content reached 10 ± 2% in order to obtain its matched dried samples. Dry OPL samples were then treated with a gum rosin using a vacuum infusion procedure, followed by a densification process. After curing, the OPL samples were trimmed and dressed to size in the form of a square cross-section of side 20 ± 1 mm and length along the vascular bundles of 300 ± 1 mm using a circular bench saw. The OPL samples were stored in a plastic bag in order to avoid moisture changes during storage. The OPL dimensions and its MC were recorded prior to bending strength tests.

Impregnation of oil palm lumber with a gum rosin

Gum rosin

Gum rosin, which is in the form of crystal was purchased from Acros Organics (M) Sdn Berhad. Being a natural organic compound, the gum rosin was dissolved with methyl ethyl ketone (MEK) (Phillips *et al.*, 1995; Erwinsyah, 2008).–Table 5.1 gives the general information pertaining to the gum rosin used.

Table 5.1: Properties of gum rosin used

Name	Concentration (%)	Viscosity (cP)	Temperature (^{0}C)
Rosin gum	60	180 ~ 210	28.2

Vacuum infusion process

The basic principles of the VI process used were similar to the process developed and the procedure outlined by Kamarudin and coworkers (2007). In general, the impregnation of gum rosin was based on equipment and procedure that uses pressure gradient to drive gum rosin into the OPL matrix (Figure 5.5).

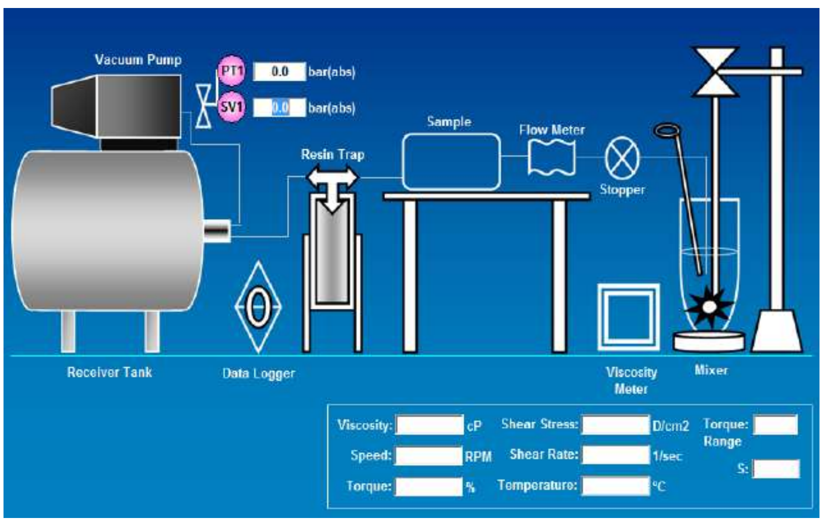


Figure 5.5: Flow process of the major stages for impregnation of oil palm lumber with gum rosin using the vacuum infusion system

To impregnate the OPL, dry lumber sample was laid in a flexible and airtight bag with certain positions being opened for gum rosin supply and outlets (Figure 3.6). Prior to infusion, the entire seals and pleats within the system was checked for leaks in order to avoid the formation of voids. This is because the process is sensitive to leakage in the flexible membrane, of which the smallest amount of air being introduced would probably result in gum rosin pooling, under-saturation, or a complete stoppage of gum rosin flow.

Figure 5.6: A prototype vacuum infusion system, specially developed for gum rosin impregnation of oil palm lumber

The vacuum was drawn first prior to the introduction of gum rosin. This operation was employed in order to extract the air from the cavity. Thereafter, a pressure difference was applied between the inlet of the flexible membrane, connected to a resin container under atmospheric pressure, and the outlet of the flexible membrane was connected to a pump under vacuum. Once a complete vacuum was achieved, the resin was literally sucked through the OPL by a reduction in vacuum pressure at the outlets, and while keeping the pressure atmospheric (101.3 kPa) at the resin inlets. To circumvent the formation of resin pooling, the flow of gum rosin within the lumber matrix was guided by the oscillating vacuum sequence, is shown in Figure 5.7.

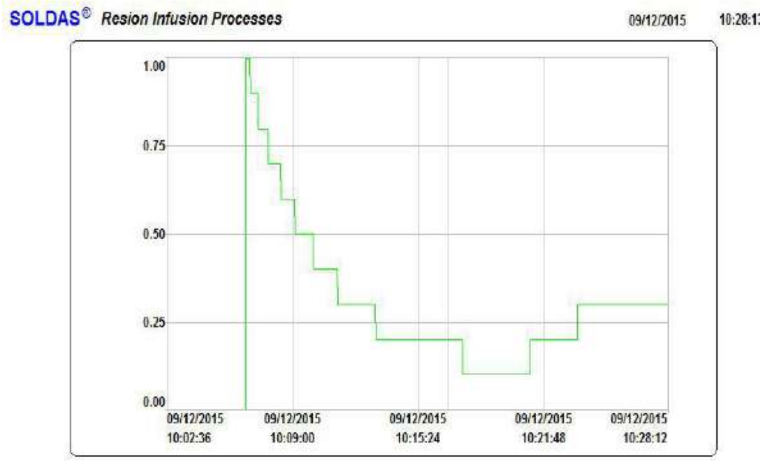


Figure 5.7: Developments of pressure gradient inside a flexible vacuum bag for gum rosin impregnation of oil palm lumber, using the vacuum infusion system

During the infusion, the impregnated part of the OPL sample was subjected to a non-uniform pressure distribution with atmospheric pressure at the inlet and vacuum at the flow front. It was noted that the compaction and the permeability of the wet area tended to vary with position and flow front progression. From observation, the OPL samples of dimensions 100 mm (thick) by 100 mm (wide) by 100 mm (long) was fully wetted with the gum rosin within 2 hours of continuous operations. At the end of the gum rosin filling time, the pressure in the bag was evened out by retaining the vacuum level at the outlets when the gum rosin supply inlet was closed.

The gum rosin-treated sample was then compressed to about 75% of its initial thickness using a cold press (Figure 5.8). This technique will remove excess gum rosin from the sample and to make it more compacted. To complete cross-linking of the gum rosin (Kamarudin *et al*., 2007), the densified gum rosin-treated OPL sample was cured under pressure in an electric oven at 60 ± 5°C for five days.

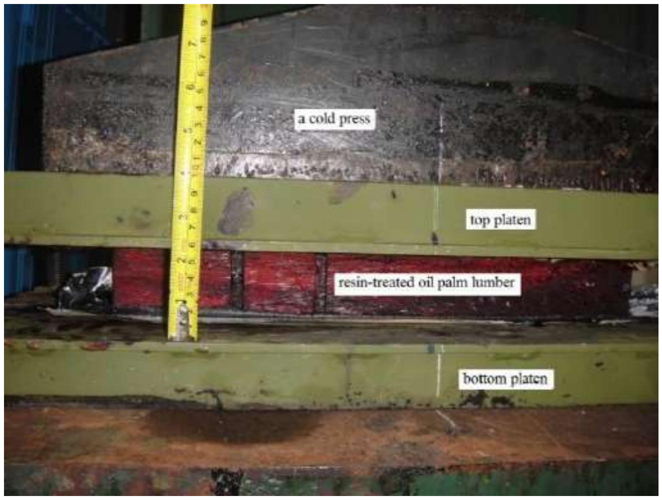


Figure 5.8: A densification process showing the compression of gum rosin -treated oil palm lumber under static load

Determination of the gum rosin penetration

Small cubic sample (in the form of a square cross-section of side 5 mm and length along the vascular bundles of 10 mm) was cut across the longitudinal direction with a razor-sharpen knife. The sample was mounted on the stub using double-sided copper tape followed by sputter coating with a 38 nm layer of gold in a vacuum evaporator in order to give it electrical conductivity for scanning electron microscopy (SEM) observation.

In the SEM, the stub (with the specimen) was tilted and rotated in all directions in order to increase the area scanned by the beam, and therefore, create perspective in the image. The penetration of gum rosin in the lumber matrix was determined from the respective photomicrographs. A Hitachi S2700 SEM operated at 15kV was used.

Evaluation of dimensional stability

Dimensional stabilization was quantified by comparing the volumetric swelling coefficients of both the densified gum rosin-treated and untreated (control) samples of OPL. Measurements of anti-swelling efficiency (ASE) were carried out by subjected to an exhaustive water-soaked treatment (Rowell and Ellis, 1978). Ten samples were used for dimensional stability test.

These samples were dried at 103 ± 2°C for 24 hours, cooled in a desiccator for 3 hours, and the three structural directions were measured. After weighing, the specimen was then vacuum-infused with distilled water until it was fully submerged. The vacuum was then released and the specimen was taken out and soaked underwater at 20 °C for 24 hours. The water-soaked dimensions were weighed and measured at the same point as the initial measurements.

Anti-swelling efficiency

An anti-swelling efficiency (ASE) value of 0 percent indicates that the treatment imparted no dimensional stability, while a value of 100 percent means that shrinkage and swelling were completely eliminated. The ASE imparted by the treatment was computed by using the equation (Mohd Saiful *et al.*, 2012):

$$\text{ASE}(\%) = \frac{S_c - S_t}{S_c} \times 100 \qquad \text{(Equation 5.3)}$$

Where S_c is the volumetric swelling coefficient of the match-sample devoid of gum rosin, S_t is the volumetric swelling coefficient of densified gum rosin-treated sample of OPL.

The volumetric swelling coefficient (S_{VC}) was calculated by using the following equation:

$$S_{VC}(\%) = \frac{V_w - V_d}{V_d} \times 100 \qquad \text{(Equation 5.4)}$$

Where, V_w is the volume of the OPL sample after soaking in m^3 while V_d denotes the volume of respective oven-dry of OPL sample in m^3 prior to soaking.

Reduction in water absorption

The reduction in water absorption (W_R) was computed by using the equation (Mohd Saiful *et al.*, 2012):

W_R (%) = [(M_c – M_t) / M_c] * 100 **(Equation 5.5)**

where M_c is water absorption of the matched OPL sample devoid of gum rosin while M_t is water absorbed of the densified gum rosin-treated OPL sample.

The water absorption (W_A) was measured by using the equation as follows:

W_A (%) = [(W_g – W_d) / W_d] * 100 **(Equation 5.6)**

where W_g is the weight of the OPL sample in g after soaking, while W_d is the oven-dry weight of OPL sample in g, prior to soaking.

Bending strength test

Strength and stiffness in bending are generally expressed as modulus of rupture (MOR) and modulus of elasticity (MOE), respectively. These properties were determined by three-point bending in accordance with ISO 3133-1975 (1975) procedures. Testing was performed in the ambient condition at 20 ± 3 °C and relative humidity of 65 ± 3% using a Zwick Testing Machine, model NNM 356. The orientation of vascular bundles in test samples was perpendicular to the direction of loading. The loading head was moved at a speed of 5 mm min^{-1} on the center of a test span of 280 mm.

The MOR and MOE were calculated using the equations as follows (ISO 3133-1975):

$$\text{MOR } (\text{N mm}^{-2}) = \frac{3P_{max} \text{ x } L}{2b \text{ x } h^2} \qquad \text{(Equation 5.7)}$$

$$\text{MOE } (\text{N mm}^{-2}) = \frac{P \text{ x } L^3}{4\Delta \text{ x } b \text{ x } h^3} \qquad \text{(Equation 5.8)}$$

where b is the breadth of the OPL in mm, h is the height of the OPL sample in mm, L is the supporting span of OPL sample in mm, P_{max} is the maximum load when the beam is broken in N, P is the load within the proportional deflection in N, and Δ is the deflection at mid-length below the proportional deflection limit in mm.

Statistical analysis

In general, data summaries were given in the tabular form. The values stated to represent the mean ± the standard error of the test results obtained. Calculations were performed with computer spreadsheet software (Microsoft Office Excel 2010 and SPSS 16.0 for Windows®). Statistical comparisons between the groups were conducted using an analysis of variance (ANOVA) and comparison among means using Scheffe's method.

Analysis of variance

Analysis of variance (ANOVA) was used to test for differences among sample means and differences among the linear combination of means. A simple application of the ANOVA was to test whether two or more sample means could have been obtained from populations with the same parametric mean. The purpose of the ANOVA was to estimate the true differences among the group means. Any single variate can be decomposed as follows (Sokal and Rohlf, 1995):

$$Y_{ij} = \mu + \alpha_i + \varepsilon_{ij} \qquad \textbf{(Equation 5.9)}$$

where $i = 1, \ldots a$, $j = 1, \ldots n$, ε_{ij} represents an independent, normally distributed variable with mean $\varepsilon_{ij} = 0$, and variance $\sigma^2_\varepsilon = \sigma^2$. Therefore a given reading is composed of the grand mean, μ of the population, a fixed deviation α_i of the mean of group i from the grand mean μ and a random deviation ε_{ij} of the jth individual of group i from its expectation, which is $(\mu+\alpha_i)$.

Comparison among means

This post-hoc statistical test was used to determine a pair of means that are not from the same population are different from each other and whether the means can be divided into groups that are significantly different from each other. Scheffe's method for comparison among mean are as follows (Sokal and Rohlf, 1995):

$$|Y_2 - Y_1| \pm [(t-1)*F(\alpha; t-1, v)*(2s^2/n)]^{1/2} \qquad \textbf{(Equation 5.10)}$$

where Y_1 and Y_2 are the sample means; s^2 is the error mean square with v degrees of freedom; $F(\alpha; t-1, v)$ is the upper (100α) % point of F-distribution with (t-1) and v degrees of freedom.

Chapter 6

Impregnation of Oil Palm Lumber with Gum Rosin

In this chapter, the research findings of important parameters from physical properties such as moisture content and basic density of oil palm trunk (OPT), and mechanical properties of strength between those of dry OPL and densified gum rosin-treated samples are reported. The studies were performed in order to assess the variability of physical properties within the trunk.

Physical properties of oil palm trunk

In general, OPT log is inherently an extremely variable material, and any consideration of its physical and mechanical properties, in a wet and dry state, must take this fact into count. One of the criticism often levied is that results of yield recovery on lumber drying and mechanical test of strength tend to be highly variable.

Moisture content

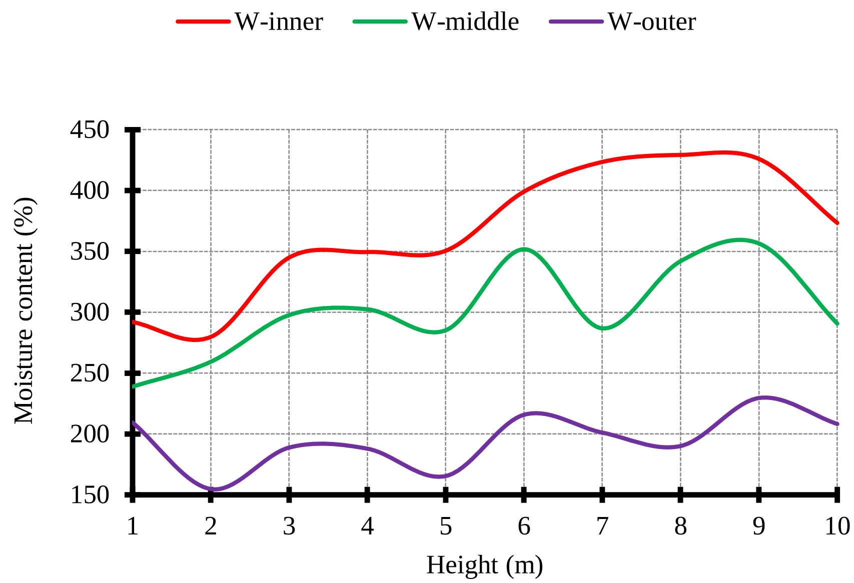
Values of mean MC in pith towards periphery zone of fresh OPT log with tree heights are given in Table 6.1. In general, variations of MC among the samples (from group A, in subgroup A-1) in the radial direction at 1-m to 6-m of tree heights are as follows: 1-m height, MC ranged between 202.65% and 292.09%; 2-m height, MC ranged between 154.64% and 92.11%; 3-m height, MC ranged between 178.75% and 349.64%; 4-m height, MC ranged between 168.51% and 349.42; 5-m height, MC ranged between 193.32% and 368.25.

Table 6.1: Mean moisture content in pith to periphery zone of oil palm trunk with tree heights (%, based on oven-dry basis)

Height (m)	Positions of test sample in pith to periphery zone		
	Inner Zone	Middle Zone	Outer Zone
1	202.65 (24.18)	238.73 (23.99)	292.09 (7.17)
2	154.64 (12.82)	104.23 (16.02)	92.11 (15.53)
3	178.75 (8.38)	297.61 (16.42)	349.64 (18.67)
4	168.51 (10.38)	302.34 (15.64)	349.42 (19.01)
5	193.32 (12.28)	285.17 (9.49)	368.25 (16.17)
6	177.26 (10.23)	351.72 (15.26)	399.06 (26.41)
7	198.61 (26.30)	286.70 (22.45)	423.40 (25.02)
8	190.12 (26.92)	341.99 (18.56)	429.12 (10.23)
9	210.61 (17.74)	356.47 (20.44)	425.82 (18.54)
10	208.23 (20.26)	290.61 (12.89)	373.30 (16.96)

Standard error of the mean is shown in parenthesis, outer (periphery) is a test sample taken at 100 mm to 150 mm from the pith, middle (intermediate) is a test sample taken at 50 mm to 100 mm from the pith and inner (pith) is a test sample taken in the pith to 50 mm in radius

The MC value at 6-m height ranged between 177.26% and 399.06%; MC at 7-m height ranged between 198.61% and 423.40%; MC at 8-m height ranged between 190.12% and 429.12%; MC at 9-m height ranged from 210.61% and 425.82% while the MC at 10-m height ranged between 208.23% and 373.30%. Figure 6.1 illustrates the MC distribution in pith towards periphery zone with tree heights. The curves indicate changes observed in the MC values for test samples of outer, middle and inner zones. As was seen for the sample position studies, these results suggest that all samples tend to show a slow gradual increase in MC as they move from the peripheral towards the inner zone with tree heights.



Outer (periphery) is a test sample taken at 100 mm to 150 mm from the pith, middle (intermediate) is a test sample taken at 50 mm to 100 mm from the pith and inner (pith) is a test sample taken in the pith to 50 mm in radius.

Figure 6.1: Spatial distribution of moisture content in pith to periphery zone of oil palm trunk with tree heights

These results suggest that it is likely the high MC at the inner and middle zones are due to the presence of parenchymatous tissues in large quantities than those of the outer zone (periphery) (Kamarudin *et al.*, 1997). Killmann and Lim (1985) has observed an initial moisture content of similar magnitude (ranging from 100% to 500%), with the highest value near the pith and the lowest value at the periphery.

In the measurement of variance (ANOVA) results taken as a stem whole, the differences in MC were significant among positions along the radial direction, $F(5, 534) = 145.76$, $p<.05$. From Table 6.2, it was clearly showed that the MC was highest in pith ranged from 359.31% to 366.73% and lowest at the periphery zone ranged from 192.03% to 195.11% while MC at the intermediate zone ranged between 290.66% and 301.06%.

A post-comparison analyses using the Scheffe post hoc criterion for significance indicated that the zone effect between the inner, middle and outer zones proved to be highly significant ($p<.05$).

Table 6.2: Variations of moisture content in pith to periphery zone of oil palm trunk

Zone	Number of specimens	Moisture content (%)			
		Min	Mean*	Max	SE
Inner	90	359.31	363.77[a]	366.73	7.56
Middle	90	290.66	295.36[b]	301.06	6.66
Outer	90	192.03	193.49[c]	195.11	4.92

*Values assigned the same letter do not statistically significant difference at 95% confidence level, SE is standard error of the mean. outer (periphery) is a test sample taken at 100 mm to 150 mm from the pith, middle (intermediate) is a test sample taken at 50 mm to 100 mm from the pith and inner (pith) is a test sample taken in the pith to 50 mm in radius

Table 6.3 shows the correlation of MC to the sample positions and height. The MC distribution and height level was positively correlated, r (540) = .28, $p<.01$, two-tailed. Pearson's correlation between the MC within OPT bole proved that the mean value of MC increased with an increase in heights. There was no significant correlation when comparing the respective value for the MC from the same spatial position and heights. However, when the variation in radial direction is considered, the MC was negatively related with sample position. These results suggest that it is likely the MC value decreases with an increase in the distance from the pith to periphery zone.

Table 6.3: Correlations of moisture content to sample positions and tree heights

	Moisture Content	Sample Position	Heights
Moisture content	—	-.03 n.s	.28**
Sample positions	-.03 n.s	—	.00 n.s
Heights	.28**	.00 n.s	—

** Correlation is significant at the 0.01 level (2-tailed); n.s denotes not statistically significant

Basic density

Table 6.4 gives the mean of BD values, in pith towards periphery zone of freshly felled OPT with tree heights. In general, variations of BD among the test samples (from group A, in subgroup A-2) in radial direction at different heights are as follows: 1-m height, BD ranged between 222.55 and 293.76 kg m^{-3}; 2-m height, BD ranged between 224.17 and 381.14 kg m^{-3}; 3-m height, BD ranged between 191.48 and 327.48 kg m^{-3}; 4-m height, BD ranged between 196.88 and 344.66 kg m^{-3}; 5-m height, BD ranged between 185.80 and 354.37 kg m^{-3}; 6-m height, BD ranged between 174.11 and 317.77 kg m^{-3}; 7-m height, BD ranged between 168.15 and 307.41 kg m^{-3}; 8-m height, BD ranged between 164.31 and 306.89 kg m^{-3}; 9-m height, BD ranged from 164.14 and 274.21 kg m^{-3} while the BD of 195.60 and 289.90 kg m^{-3} was located at the 10-m height level.

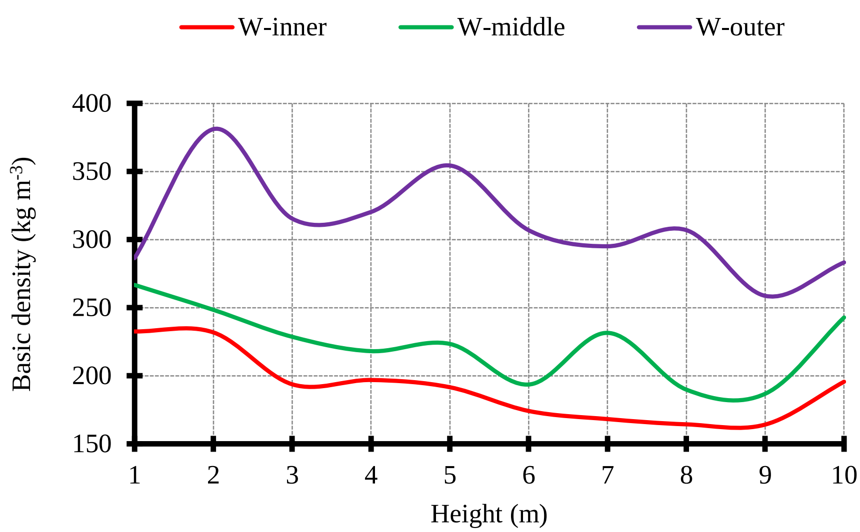
The BD distributions in pith towards periphery zone of OPT with heights is shown in Figure 6.2. The curves indicate that test samples obtained from the pith seemed to having the highest value at periphery zone and the lowest value in pith.

Table 6.4: Mean basic density in pith to periphery zone of oil palm trunk with tree heights (kg m^{-3})

Height (m)	Positions of Test Sample, in Pith to Periphery Zone		
	Inner Zone	Middle Zone	Outer Zone
1	222.55 (16.31)	266.65 (21.74)	293.76 (15.95)
2	224.17 (5.53)	248.35 (11.57)	381.14 (31.73)
3	191.48 (2.28)	228.57 (11.97)	327.48 (19.10)
4	196.88 (3.42)	218.04 (6.14)	344.66 (19.94)
5	185.80 (5.51)	223.34 (3.87)	354.37 (23.31)
6	174.11 (4.16)	193.57 (7.79)	317.77 (38.72)
7	168.15 (10.34)	231.46 (17.98)	307.41 (6.88)
8	164.31 (7.98)	189.80 (11.69)	306.89 (14.93)
9	164.14 (6.02)	186.80 (9.23)	274.21 (8.86)
10	195.60 (9.75)	242.78 (13.86)	289.90 (6.37)

Standard error of the mean is shown in parenthesis, outer (periphery) is a test sample taken at 100 mm to 150 mm from the pith, middle (intermediate) is a test sample taken at 50 mm to 100 mm from the pith and inner (pith) is a test sample taken in the pith to 50 mm in radius

As was seen for the sample position studies (Figure 6.2), these results suggest that all samples tend to show a gradual decrease in BD as the sample positions move from peripheral towards inner zone with tree heights. These results suggest that it is likely the high BD at the outer and middle zones are associated with the presence of parenchymatous tissues in lower amounts compared to the inner zone.



Outer (periphery) is a test sample taken at 100 mm to 150 mm from the pith, middle (intermediate) is a test sample taken at 50 mm to 100 mm from the pith and inner (pith) is a test sample taken in the pith to 50 mm in radius

Figure 6.2: Spatial distribution of basic density in pith to periphery zone of oil palm trunk with tree heights

Table 6.5 shows the mean BD value in pith to periphery of OPT. These results suggest that the BD was highest at the periphery zone ranging between 311.78 and 314.43 kg m^{-3} and lowest in pith ranging between 191.12 and 103.34 kg m^{-3}, while BD at the middle zone ranged between 222.25 and 230.23 kg m^{-3}.

Table 6.5: Variations of basic density in pith to periphery zone of oil palm trunk

Zone	Number of Specimens	Basic Density (kg m^{-3})			
		Min	Mean*	Max	SE
Inner	87	191.12	103.34^{a}	299.75	3.56
Middle	87	222.25	227.11^{b}	230.23	4.67
Outer	87	311.78	312.59^{c}	314.43	7.21

*Values assigned the same letter do not statistically significant difference at 95% confidence level, SE is standard error of the mean, outer (periphery) is a test sample taken at 100 mm to 150 mm from the pith, middle (intermediate) is a test sample taken at 50 mm to 100 mm from the pith and inner (pith) is a test sample taken in the pith to 50 mm in radius

Table 4.6 shows the correlations of BD to the position of test samples and heights. The BD distribution was negatively correlated with heights, r (522) = -.26, p<.01, two tailed. This proves that the mean value of BD decreased with an increase in heights. There was no significant correlation when comparing the respective value for BD from the same spatial position. However, when the variation in radial direction is to be considered, BD (r = -0.04) was negatively related with sample positions (periphery to pith). This means that it is likely the value of BD decreases from periphery zone (E-outer and W-outer) towards the pith (E-inner and W-inner).

Table 6.6: Correlations of basic density to sample positions and tree heights

	Basic Density	Sample Positions	Heights
Basic Density	—	-.04 n.s	-.26**
Sample positions	-.04 n.s	—	.00 n.s
Heights	-.26**	.00 n.s	—

** Correlation is significant at the 0.01 level (2-tailed); n.s denotes not statistically significant

In general, the mean value of BD ranges from 191.12 to 314.43 kg m^{-3} with no defined zones of increasing or decreasing densities in radial direction. It is rather apparent that the OPT is composed of the so-called juvenile woody materials (densities of 250 kg m^{-3} and below), which is generally defined as a zone developing around the pith continuing towards the outer perimeters where its characteristics and properties are subject to gradual changes (Zobel and Sprague, 1998). The woody section of higher densities was concentrated in the periphery zone and partly in the intermediate zone. Depending on tree heights, the OPT log with the BD of 250 kg m^{-3} and above, is mainly located outside a distance of 86 to 139 mm radius from its pith.

Impregnation of oil palm lumber with a gum rosin

The successful performance of a bonded OPL product is the degree of wetting of gum rosin used. Like other types of wood adhesive, the gum rosin will stay bound together if the degree surface tension value of the gum rosin is greater than the surface-free energy value of OPL substrate. Conversely, when the surface-free energy value of the OPL substrate is higher than that of the gum rosin it allows the gum rosin to uniformly wet the OPL surfaces.

Sulaiman and co-workers (2009) mentioned that the contact angle on the surface of oil palm veneer was lower than the rubberwood. High wettability for OPL is partly due to high content of ground parenchyma cells, which will result in better penetration of gum rosin. A positive linear relationship was developed between the surface wettability and glue bond strength for bond integrity (Chen *et al.*, 1970).

Penetration of gum rosin into the lumber matrix

The vacuum infusion (VI) process used seemed to work well for the impregnation of OPL with gum rosin and it entered the lumber sample at a fixed point where the path resistance of gum rosin flow was minimum. The sample surface caused in micro-flow which progress between the vascular bundles and its parenchyma tissues, resulting in a non-homogenous flow front at the sample ends to that of the gum rosin. The resulting distance between the flow fronts is called lead-lag, is shown in Figure 4.3. The length of the lead-lag depends mainly on the permeability and the surface area of the sample used (Gabrielli and Kamke, 2010).

Permeability is a geometric parameter of OPL, which quantify how easily the gum rosin will flow through it. This geometric parameter is taken into account the porosity, which is the amount of void space in the OPL and is related to fibre volume fraction (Lopatnikov *et al.,* 2004). In resin infusion process, the higher the permeability suggests relatively shorter vacuum suction time is required, which may impose some limitations particularly if the gum rosin used is viscous.

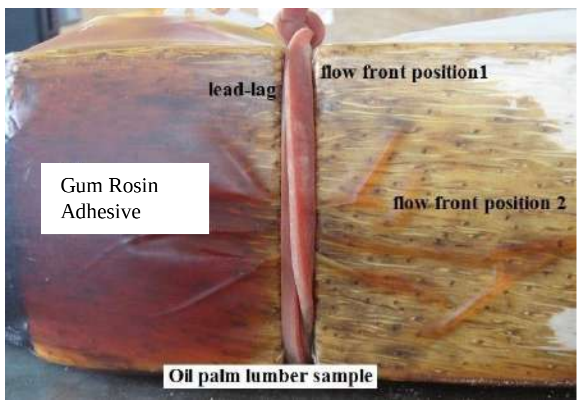


Figure 6.3: Creation of a lead-lag within the matrix of oil palm lumber during the resin impregnation process

For the VI process, the OPL sample (dimension: 100 mm wide by 100 mm thick by 400 mm long) took approximately two hours for wetting of the lumber matrix completely with the gum rosin. Too shorter the vacuum time would result in insufficient penetration and transfer of gum rosin whilst too long would cause the resin to pre-cure. One problem encountered with the presence of a lead-lag (Lee and Wei, 2000) is that the sample ends in contact with the gum rosin is fully filled before the rest of parts. If gum rosin gelation occurs before the sample is fully impregnated, a dry patch remain in the sample.

The precise reason for resin impregnation was not clearly understood. It was difficult to apply the Darcy's equation to directly predict and measure permeability because of the challenges in controlling all the variables (Patel *et al*., 1995). For instance, OPL sawn from the same positions and heights of OPT possessed a significantly different microstructure, and therefore, will influence the permeability of the lumber sample (Waterhouse and Quinn, 1978).

Initially, problems of continuous resin flow within the matrix of dried lumber seemed unavoidable. It was noted that drying of OPL causes its surfaces to be 'inactivated' to resin flow due to (a) exudation of extractives to the surface, which lowers the wettability or hides the surface, (b) reorientation of wood surface molecules, which reduces wettability or bonding sites, and (c) irreversible closure of large micropores in cell walls (Christiansen, 1990).

Moreover, at the beginning of resin infusion, the stiffness of lumber sample could resist the compressive force of atmospheric pressure. The internal pressure, however, changes during the course of infusion, which in turn, will indirectly lead to changes in the permeability of the lumber sample due to compaction of the sample under vacuum (Barraza *et al.,* 2004).

One approach to direct the flow of resin homogenously within the lumber sample is to incise its surfaces with narrow grooves and channels (10 mm long) at the sample ends is shown in Figure 6.4. Provided the incisions are not too frequent the lumber is not weakened and the gum rosin can enter the lumber through the exposed ends in each incisions under vacuum treatment, and form an envelope of treated wood, which is slightly deeper than the incisions.

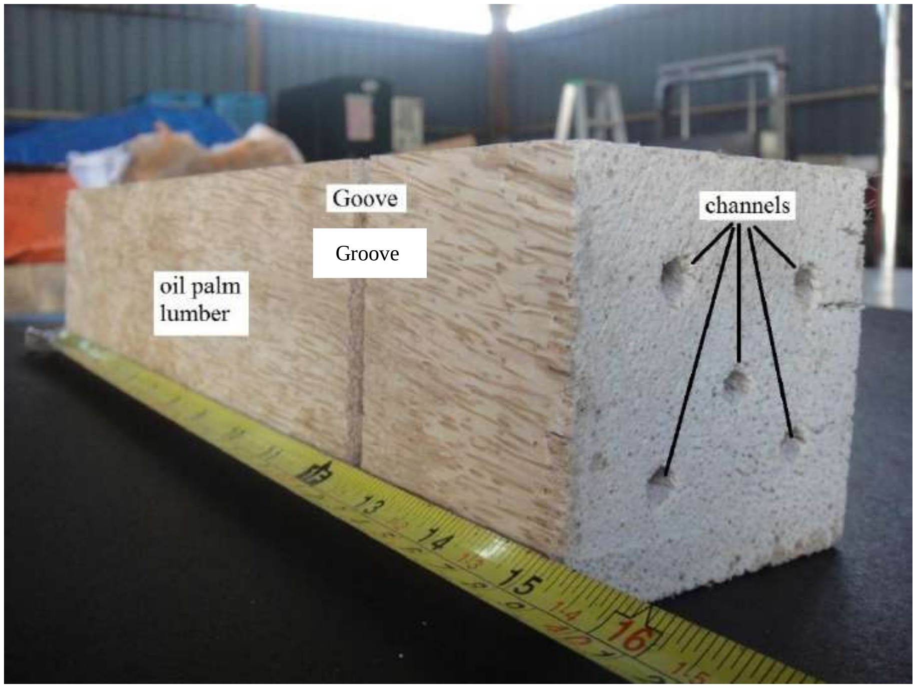


Figure 6.4: Positions of groove and channel to ease the flow of resin used into the matrix of oil palm lumber

It was noted that the gum rosin used was dispersed homogenously within the matrix of lumber sample. Such technique tended to eliminate the formation of resin-rich or starved areas and dry patches within the sample, and therefore leads to the success of resin infusion. For the OPL samples, mean amount of gum rosin absorbed and the time taken to infuse the resin per unit volume of the lumber sample was 0.69 g cm^{-3} and 1.5 s cm^{-3}, respectively.

Effect of gum rosin and densification treatments on dimensional stability

The anti-swelling efficiency (ASE) values, which was calculated on a volumetric basis and represent the amount of swelling that gum rosin resin treatment prevents when compared to the swelling of a control samples, show that the low molecular weight gum rosin resin was able to impart a degrees of stability to the densified gum rosin -treated OPL. The densified gum rosin -treated OPL yielded ASE values (Table 6.7), are as follows: Outer zone ranged from 3.58% to 26.11%; Inner zone ranged from 0.96% to 10.07% while ASE values ranged between 1.20% and 10.02% for Middle zone.

Table 6.7: Variations of dimensional stability in pith to periphery zone of densified gum rosin-treated oil palm lumber

Zone	Number of Specimens	Anti-swelling Efficiency (%)			
		Min	Mean*	Max	SE
Outer	9	3.58	8.53[a]	26.11	2.46
Inner	9	0.96	4.75[b]	10.07	1.07
Middle	9	1.20	6.48[b]	10.02	1.04

*Values assigned the same letter do not statistically significant difference at 95% confidence level, SE is standard error of the mean, outer (periphery) is a test sample taken at 100 mm to 150 mm from the pith, middle (intermediate) is a test sample taken at 50 mm to 100 mm from the pith and inner (pith) is a test sample taken in the pith to 50 mm in radius

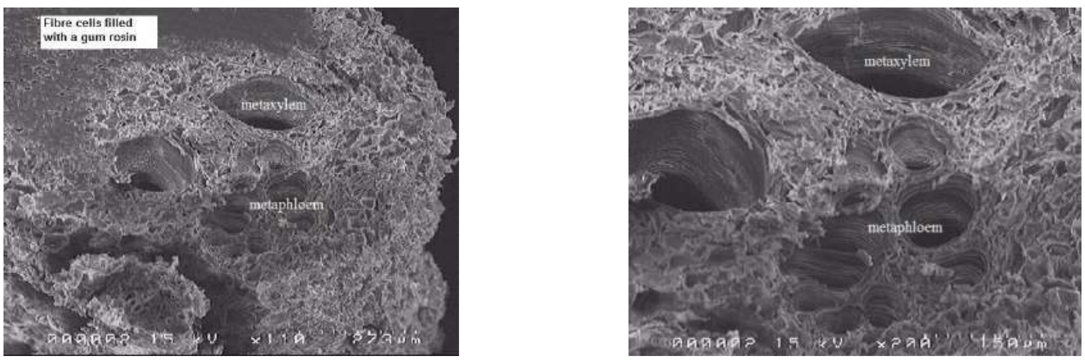
The positive ASE value indicates that the gum rosin had penetrated into the cell wall and subsequently cross-linked, leading to bulking along interstitial spaces (Loh *et al.*, 2010) created when thin-wall parenchyma cell collapse during drying (Obataya *et al.,* 2004). Gum rosin is located mostly in the cell wall of vascular bundles and yields dimensionally stable composites (Kumar, 1994).

The amount of water absorption was reduced by 75.22% to 79.09% (Table 4.8). It was noted that polymer grafting may have been taken place with reactive group on OPL component within the cell wall while ungrafted bulk polymer was formed in the OPL voids (Rowell *et al.*, 1982). The gum rosin used was deposited either in cell-lumen (Schneider, 1995), in cell-wall (Furano *et al.*, 1992) or a combination of cell-lumen and cell-wall types (Schneider *et al.*, 1991). A typical SEM image of the vascular bundles of gum rosin-treated sample is shown in Figure 4.5.

Table 6.8: Variations of water reduction in pith to periphery zone of densified gum rosin-treated oil palm lumber

Zone	Number of Specimens	Amount (%)			
		Min	Mean*	Max	SE
Outer	9	60.25	75.22[a]	90.24	3.79
Inner	9	65.24	80.33[a]	97.95	3.47
Middle	9	68.42	79.09[a]	98.92	3.54

*Values assigned the same letter do not statistically significant difference at 95% confidence level, SE = standard error of the mean, outer (periphery) is a test sample taken at 100 mm to 150 mm from the pith, middle (intermediate) is a test sample taken at 50 mm to 100 mm from the pith and inner (pith) is a test sample taken in the pith to 50 mm in radius



(a) VB filled with a gum rosin (X80) (b) VB filled with a gum rosin (X150)

Figure 6.5: Typical SEM photomicrographs showing the distribution of gum rosin within the vascular bundles of densified gum rosin-treated oil palm lumber

Flexural strength of oil palm lumber

Dried oil palm lumber

Table 6.9 gives the mean values of MOR and MOE, in pith towards periphery zone of matched dried OPL samples (from group B, in subgroup B-1). In general, variations of the MOR and MOE among the samples in radial direction with height are as follows: 2-m height, MOR ranged between 13.13 to 24.68 MPa and MOE ranged between 2,131.54 to 4,007.32 MPa; 4-m height, MOR ranged between 10.97 to 20.29 MPa and MOE ranged between 1,781.61

to 3,295.09 MPa while the MOR and MOE at 6-m height ranged between 7.26 to 19.22 MPa, and 1,178.23 to 3,120.83 MPa, respectively.

Table 6.9: Mean flexural strength in pith to periphery zone of dry untreated oil palm lumber with tree heights

Height (m)	Sample positions					
	Outer Zone		Pith		Middle Zone	
	MOR (MPa)	MOE (MPa)	MOR (MPa)	MOE (MPa)	MOR (MPa)	MOE (MPa)
2	24.68	4,007.32	13.13	2,131.54	20.65	3,352.19
	(2.68)	(435.67)	(1.04)	(168.11)	(1.16)	(187.73)
4	20.29	3,295.09	10.97	1,781.61	18.78	3,049.12
	(1.86)	(302.06)	(1.04)	(162.69)	(1.27)	(206.14)
6	19.22	3,120.83	7.26	1,178.23	16.75	2,719.53
	(2.55)	(414.28)	(0.31)	(49.92)	(1.31)	(212.05)

Standard error of the mean is shown in parenthesis, MOR is modulus of rupture, and MOE is modulus of elasticity, outer (periphery) is a test sample taken at 100 mm to 150 mm from the pith, middle (intermediate) is a test sample taken at 50 mm to 100 mm from the pith and inner (pith) is a test sample taken in the pith to 50 mm in radius

In general, mean MOR and MOE values were higher at the periphery zone and lower in pith. This indicates that the OPL from woody portion at 100 mm from the periphery was significantly stronger than those woody portion located in pith.

For OPT log, a decreasing trend in flexural strength properties was apparently going from the outer regions towards the pith. This proved that the strength of woody portion was highly dependent on the variation in moisture content and their basic density values (Kamarudin *et al.*, 2011). The result highlighted the need to effectively grade to ensure the desired strength properties specific to product needs are capitalised upon in order to determine structure serviceability.

Densified gum rosin-treated oil palm lumber

Mean values for MOR and MOE of OPL scantling (from group B, in subgroup B-2), taken in pith towards periphery zone in east and west directions with tree heights, and treated with gum rosin is given in Table 6.10. In general, variations of the MOR and MOE among the samples in radial direction with height are as follows: 2-m height, MOR ranged between 18.31 to 43.21 MPa and MOE ranged between 2,972.41 to 7,015.85 MPa; 4-m height, MOR ranged between 14.98 to 39.89 MPa and MOE ranged between 2,432.63 to 6,476.53 MPa while the MOR and MOE at 6-m height ranged between 15.08 to 34.15 MPa, and 2,448.75 to 5,544.52 MPa, respectively.

Table 6.10: Mean flexural strength in pith to periphery zone of densified gum rosin-treated oil palm lumber with tree heights

Height (m)	Sample positions					
	Outer		Pith		Middle	
	MOR (MPa)	MOE (MPa)	MOR (MPa)	MOE (MPa)	MOR (MPa)	MOE (MPa)
2	43.21 (3.34)	7,015.85 (541.59)	18.31 (1.83)	2,972.41 (297.89)	42.68 (2.77)	6,930.23 (449.56)
4	39.89 (4.13)	6,476.53 (670.69)	14.98 (1.75)	2,432.63 (283.33)	31.47 (1.24)	5,109.91 (201.74)
6	34.15 (2.63)	5,544.52 (427.63)	15.08 (1.33)	2,448.75 (216.19)	32.92 (3.17)	5,344.33 (515.70)

Standard error of the mean is shown in parenthesis, MOR is modulus of rupture, and MOE is modulus of elasticity, outer (periphery) is a test sample taken at 100 mm to 150 mm from the pith, middle (intermediate) is a test sample taken at 50 mm to 100 mm from the pith and inner (pith) is a test sample taken in the pith to 50 mm in radius

Based on results, the strength of densified gum rosin-treated OPL had increased by approximately 66% more than those of the same matched dry OPL samples. This indicates that sufficient amount of gum rosin had penetrated and bulked into the OPL using the vacuum infusion technique, and followed by a densification process. It was noted that most of bending samples failed normally, first in compression followed by a simple tension. It is believed that the presence of gum rosin (which is either cross-linked with the cellulose or bulked the fibre walls), increased the support of the samples and reduced their buckling under the compressive load (Fry, 1976).

The histogram (Figure 6.6) serves to reduce and consolidated the data collected of MOR and MOE values of dry-versus densified gum rosin-treated samples of OPL scantling with tree heights, in this series of mechanical properties of strength studies. The lengths of the bars shown indicate the distance of respective strength value in terms of the geometric mean measurements, from the pith to periphery zones, expressed as a unit.

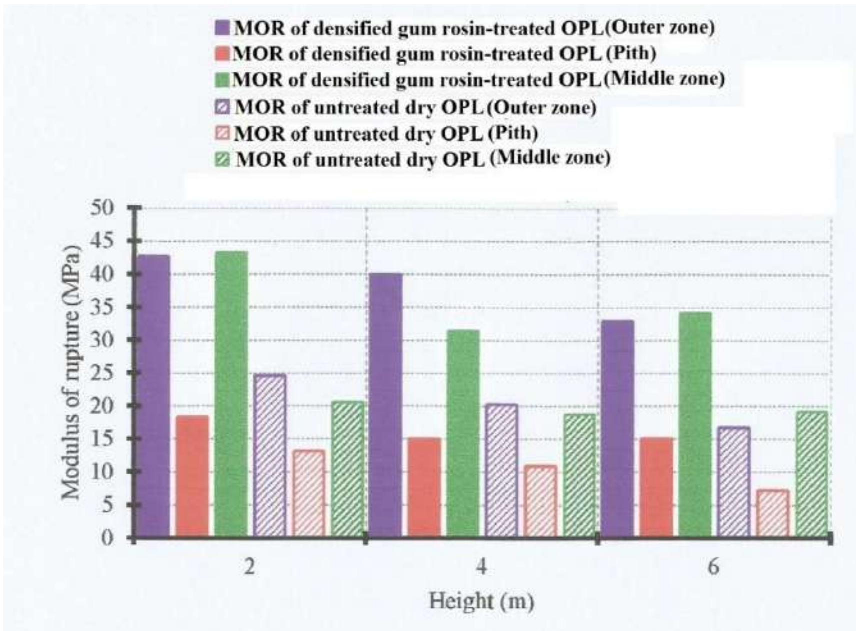


Figure 6.6: Values of modulus of rupture in pith to periphery zone of densified gum rosin-treated and matched dry oil palm lumber with tree heights

Treating the data in this manner makes it possible to compare the degree of variations to which the various OPL scantlings retain each of the observed mechanical properties of strength. Hence, the need to portray the results of variation in strength properties more than just one style. From this histogram, the expected mechanical properties of strength for each individual test samples in relation to treatment types could be identified. This data was recorded in the summary table, which appear in Tables 4.9 and 4.10. It was then possible to use these values to calculate the changes in strength properties of interest, in order to facilitate comparison of within-treatment types in a more quantitative approach.

Conclusion

Basic properties-related parameters that include variations of MC and BD, in pith to periphery zone of high yielding tenera (a hybrid between those of dura and pisifera) palm with tree heights were identified. Based on results, the MC in pith and its intermediate zones (ranging from 359.31% to 366.73%) were higher than the MC of periphery zone (ranging from 192.03% to 195.11%). The BD increased from the vicinity of the pith (ranging from 191.12 to 299.75 kg m^{-3}) towards the periphery zone (between 311.78 and 314.43 kg m^{-3}). The main adverse effect of this variability is the gradient in radial position with tree heights, which will greatly influence processing, production output and the product quality. For oil palm, the dependency of MC and BD differed with heights, but did not significantly differ between test samples of similar position along its diameter. Based on basic properties estimates, it is therefore possible to predict the exact position of usable raw materials for specified end uses For example, OPT of high density (250 kg m^{-3} and above) with the lowest MC (300% and below) is located outside a distance of 139 mm radius from the pith. The OPL scantling was impregnated with a gum rosin using a prototype VI (vacuum infusion) system. With regards the resin infusion, it was noted that the gum rosin flow is directly proportional to the permeability of OPL macrostructure and the pressure difference between the inlet and outlet, but inversely proportional to the gum rosin viscosity. After compensating some changes to the OPL scantling (with the introduction of grooves and channels), the gum rosin was homogenously dispersed within the lumber structure. The positive ASE (antiswelling efficiency) values proved that the gum rosin had penetrated into the cell wall. As for flexural strength properties, the magnitude of MOR (modulus of rupture) and MOE (modulus of elasticity) were directly related to the BD value, but inversely correlated to the MC gradient. In general, the strength of densified gum rosin-treated lumber increased to approximately 66% compared to dry OPL samples.

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