CHAPTER II

LITERATURE REVIEW

2.1 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 fibreboard, (c) wooden mouldings, 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, Republic of Korea at RM 954.34 million, Republic of Singapore at RM946.87 million, Australia at RM905.23 million, 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 in order 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 utilised rubberwood, which are sourced from sustainable plantations as raw materials for furniture and panel products (MPIC, 2009).

2.1.1 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 crops. 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. In accordance with 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 facing 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 in conserving the country's forest resources for the benefit of the present and future communitie's livelihood (Birka *et al.,* 2011).

2.1.2 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 be 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 year 2010 onwards (MPIC, 2009). Nevertheless total log production from natural forest, 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 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, labour 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 biocomposite 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 fibre materials are available from the agricultural sectors. These fibre and biomass materials range from rice husks, coconut trunk fibres, kenaf to oil palm biomass in the form of oil palm trunk (OPT), 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 biocomposites manufacturing portfolio but also for accommodating other downstream economic activities such as the electricity generation (AIM, 2011).

2.2 Oil Palm Industry in Malaysia

As the Malaysian economy continues to expand and develop further, the palm and oil sectors has played an active and important role in the supply of palm oil and palm products as raw material for the further development of the industrial, commercial and service sectors. In fact, oil palm tree is the major commodity crop in Malaysia due to the country's Agriculture Diversification Policy to minimise 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).

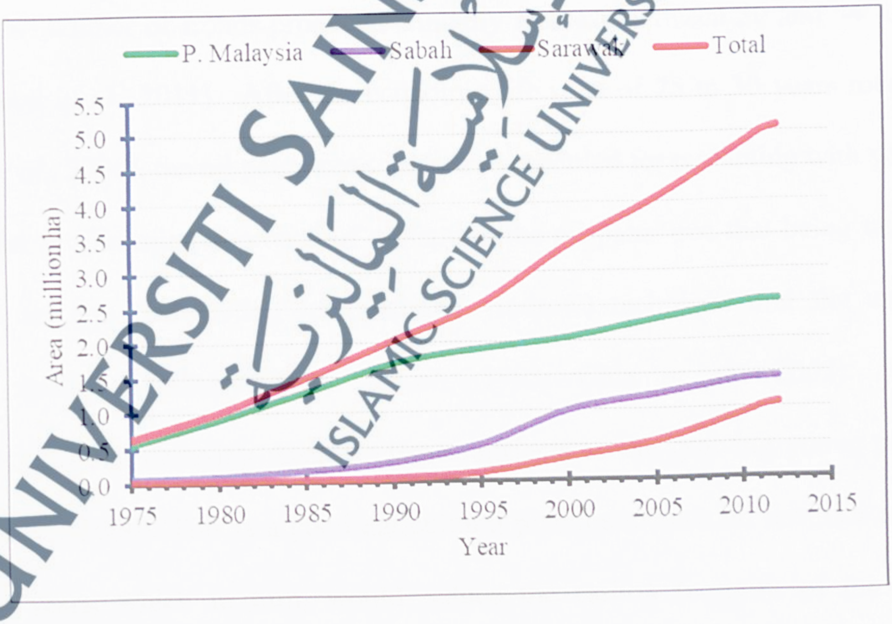


Figure 2.1: Trends of increased oil Palm tree planted hectarage for Peninsular Malaysia, Sabah and Sarawak from 1975-2013 (MPOB, 2014)

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).

2.2.1 Oil palm replanting regime

The height increment of 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 increase 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 being widely practiced are 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 fertiliser 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 seedling 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 very high breeding ground of rhinocerous beetles (*Oryctes rhinocerous*) 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 rhinocerous*, 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 large amount 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 fibre-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.

2.3 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 supply 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).

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

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 term of the palm tree, this 'saved' investment can be diverted to more appropriate ecological events, such as growing in height, or in reproduction (Dransfield *et al.*, 2008).

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 present of stegmata, adjacent to fibrous sheaths and strands. Stegmata are 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 fibres (Weiner and Liese 1990).

2.3.1 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 is 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 replanting age of a 25-year rotation, the bole length of high yielding *Tenera* palm is 9 to 13 m long with the mean volume of 1.76 m^3 (Kamarudin *et al.*, 1997). The OPT density vary 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 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 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 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 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 amount 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 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 resemble "monkey faces" (Figure 2.6) (Kamarudin *et al.*, 2011).

Figure 2.6: SEM Photomicrograph showing a cross-section of 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 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 fibres. In general, the length of OPF fibres from mature oil palm is found to be longer than those fibres from young oil palm. The average length of OPT fibres, ranges from 1.23 to 1.37 mm while those fibres from OPF and EFB ranges 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 a ground parenchyma, special features cells, so-called ducts, occur. These cell possess thin unlignified walls and are either arranged solitarial or in small cluster. In the longitudinal section observed bundles of raphides in the ducts. These cells are referred as 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 *p*-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 affects overall utilisation of the oil palm trunk and may alter processing characteristics.

2.4 Use of Wood for Sawn Lumber and Biocomposites

Tree that grow quickly in their early years, or 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 cause distortion on drying. The trees harvested at short rotations are much younger and tend to be smaller size than those from natural forests. Despite this, there is a greater need to utilise 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 are 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).

2.4.1 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 shrub (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.

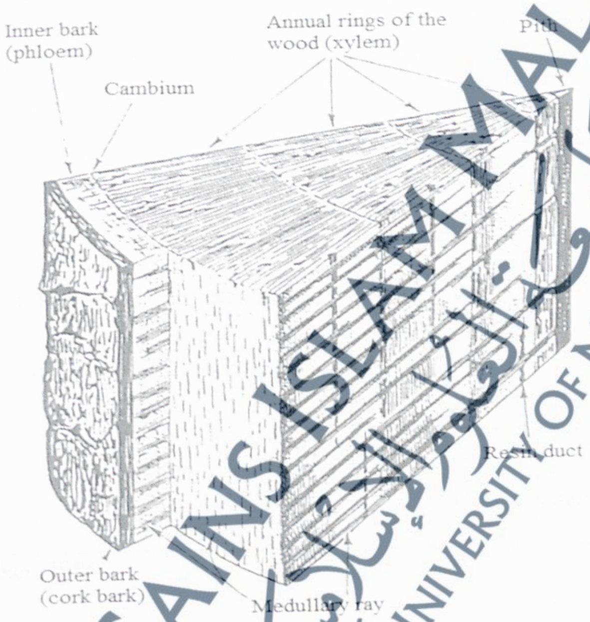


Figure 2.7: A schematic section of a four year old pine stem (Rydholm, 1965)

All these phenomena are a result of the growth and development of the wood tissue, 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 2.3 and Figure 2.8) (Fengel and Wegner, 1984).

Table 2.3: 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)

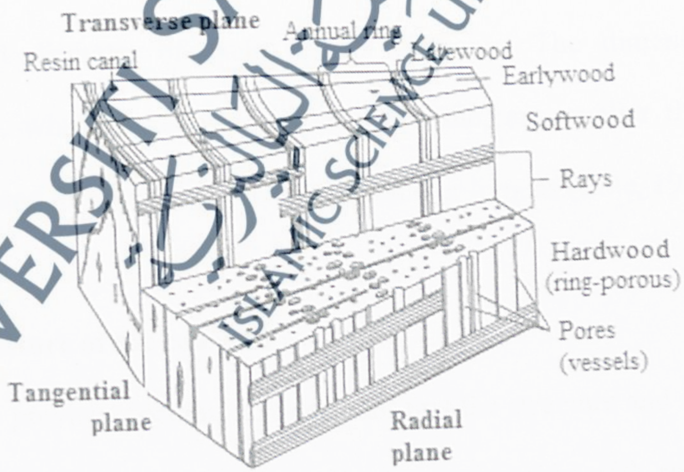


Figure 2.8: Models of a softwood and a hardwood block, showing the main cutting planes for anatomical studies, and anatomical structures visible without optical aids (Fengel and Wegner, 1984)

Softwoods show relatively simple structure, 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 become smaller while the cell wall become 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 to the eye 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).

2.4.2 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 become 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).

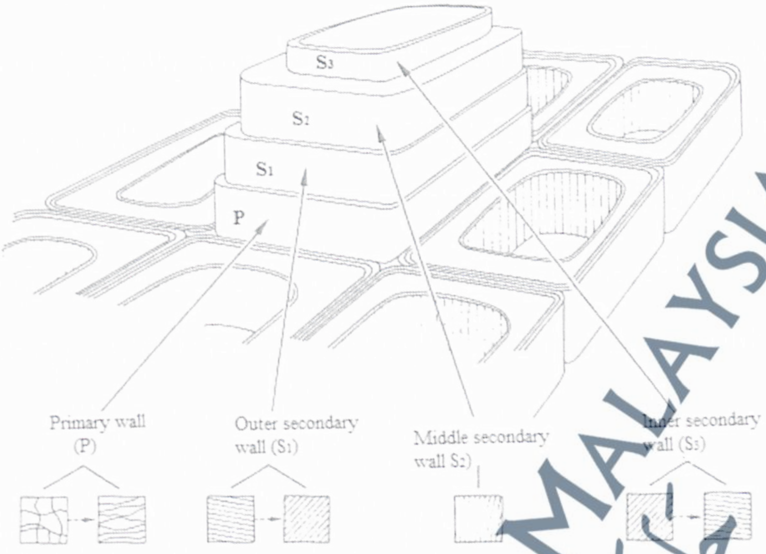


Figure 2.9: Structure of the cell wall of a typical softwood tracheid (Emerton, 1980)

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 crossgartered 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 technological unimportant (Cote, 1965).

2.4.3 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 component of wood (Fengel and Wegner, 1984).

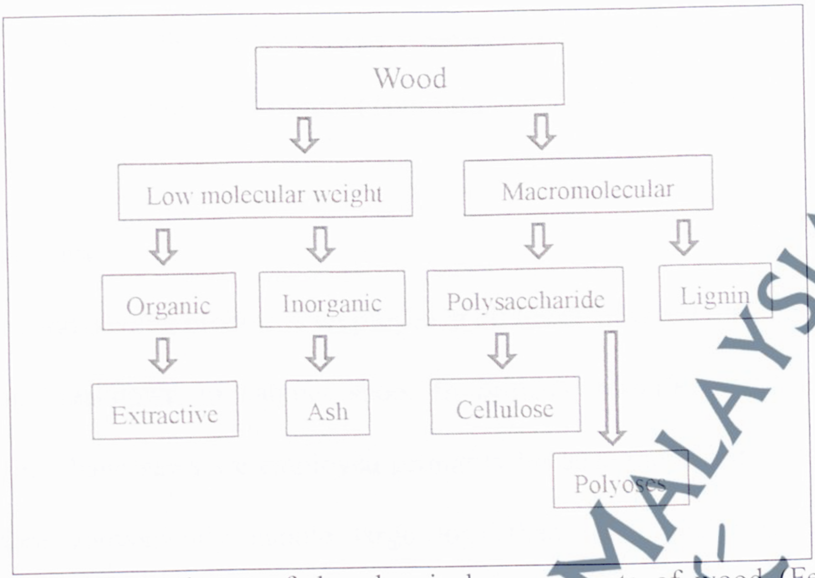


Figure 2.10: General scheme of the chemical components of wood (Fengel and Wegner, 1984)

2.5 Sawmilling Processes

2.5.1 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 resaws, 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).

2.5.1.1 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 sawing 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 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).

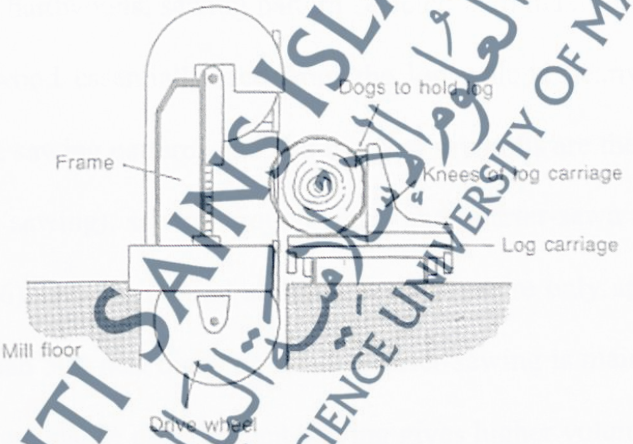


Figure 2.11: Schematic diagram of a bandsaw attached with log carriage (Williston, 1988)

2.5.2 Sawing of sawn lumber

2.5.2.1 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.

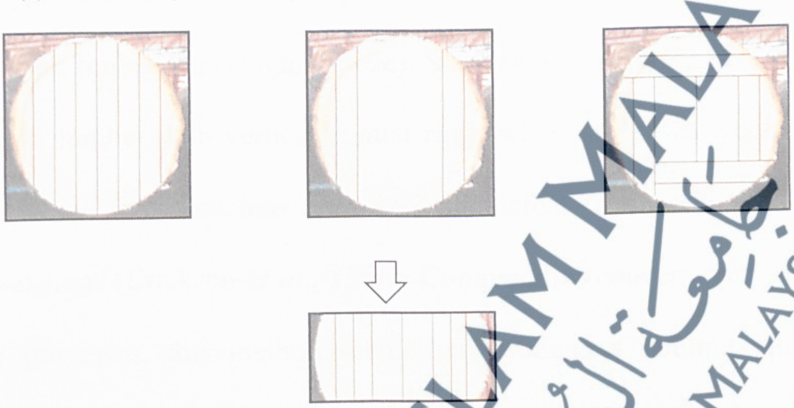
The quality and value of sawn lumber are largely determined during the sawing process, of which the sawing pattern employed provides the basis for a profitable production of sawn lumber. In general the sawing pattern will affect the yield from the log, the grade of the sawn lumber and the sawmill productivity. 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).

Denig and Wengert (2005) stated that live-sawing pattern (Figure 2.12a) 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 2.12b) 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).

(a) Live-sawing (b) Square-sawing (c) Sawing-around



(d) 3-ex-log (e) Monolit-sawing (f) Star-sawing

(g) Quarter-sawing

Figure 2.12: Examples of sawing pattern adopted for the primary breakdown of timber log (Erickson *et al.*, 1986)

The sawing-around pattern (Figure 2.12c) 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 2.12d 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).

2.6 Anisotropic Shrinkage and Swelling of Wood

Perhaps the biggest limiting factor in timber usage is their lack of dimensional stability upon drying. Wood distortions is 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).

2.6.1 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).


(a) Cup/diamond

(b) Bow


(c) Crook

(d) Twist

Figure 2.13: 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).

2.7 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) are 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 application of heat to impregnation with monomers or prepolymers for *in situ* polymerisation, 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).

2.7.1 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 2.14: 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 adherend 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 analysis 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).

2.7.1.1 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).

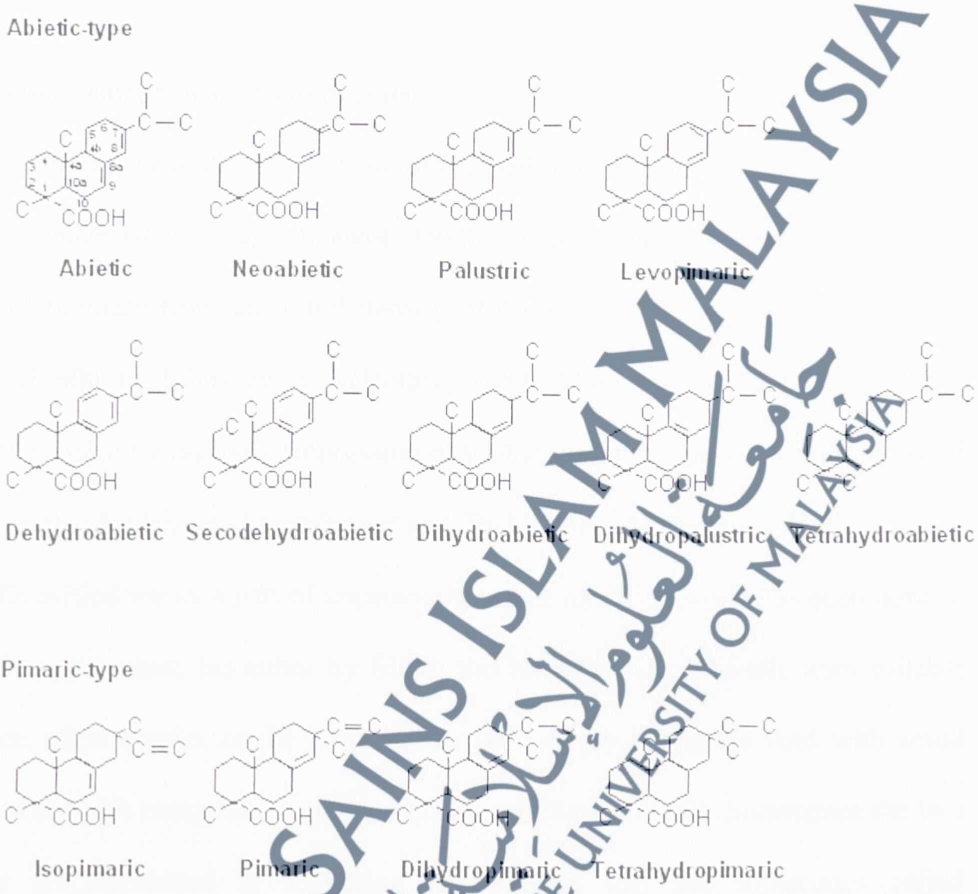


Figure 2.15: Chemical compositions of gum rosin

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.

2.7.2 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. This study 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).

2.7.3 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 under-graded 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.

In a study conducted by 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.

2.8 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$^{\text{TM}}$). 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).

2.9 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).