CHAPTER 1

INTRODUCTION

1.1 Introduction

This thesis reports upon studies of the water vapour sorption properties of wood. The work used a Dynamic Vapour Sorption (DVS) apparatus, which is an instrument that was initially used for the investigation of pharmaceutical materials and has not been used for the study of wood and wood products until very recently. This work is the most comprehensive study of wood sorption properties using DVS to date. The DVS can be used not only to determine the equilibrium moisture content (EMC) of wood at different values of atmospheric relative humidity (RH), but also allows for kinetic studies to be undertaken. In the past, such studies have required complex and expensive apparatus to obtain accurate data and as a result the data sets have often been of poor quality. The DVS can provide large amounts of kinetic data very easily and rapidly. Much of the sorption kinetic data is currently interpreted in terms of Fickian (i.e. diffusion limited) models, but with swelling materials (such as wood) such an interpretation is invariably incorrect. The polymer science literature interprets sorption kinetics behaviour in swelling materials as being relaxation limited and this type of model has been investigated in this study. The sorption kinetics was evaluated using a parallel exponential kinetics (PEK) model. This model was first applied to the study of the sorption behaviour of flax and subsequently to cellulose, but has not until very recently been applied to the study of wood, or wood products. The sorption isotherm of wood and many other natural materials exhibits hysteresis; that is the adsorption and desorption branches

of the isotherm differ. Although many models exist that attempt to explain this behaviour, in reality the phenomenon is not understood. However, within the polymer science literature the phenomenon is explained in terms of molecular relaxation processes taking place below the glass transition temperature (*Tg*). From this it is possible that there may be a link between the kinetic and equilibrium sorption states, since both processes may be linked to polymer relaxation processes. The PEK equation allows for the determination of characteristic times for the two kinetic processes (termed fast and slow), the reciprocals of which give rate constants. From these, the Arrhenius expression can be used to determine activation energies and entropies and from these the Gibbs free energies of sorption can be determined. From such a study it may be possible to further our understanding of what hysteresis is. This work was undertaken to further our understanding of the sorption kinetics and hysteresis behaviour of wood.

The structure of the thesis is as follows:

1. Chapter 1 covers the introduction, the objectives of the study and general information of wood.
2. Chapter 2 describes the literature review on water vapour sorption behaviour on wood including sorption isotherms, hysteresis, sorption kinetics, activation energy and wood modification.
3. Chapter 3 deals with the preliminary studies on DVS data reproducibility, sorption isotherms, hysteresis, analysis with the Hailwood-Horrobin (H-H) model and comparison of the availability of water molecules per sorption

site through macromolecular composition and primary sorption sites/monolayer water.

4. Chapter 4 describes the effect of different tropical hardwoods and thermally modified wood in sorption isotherms, hysteresis and analysis with H-H model.
5. Chapter 5 describes sorption kinetics analysis using the parallel exponential kinetics (PEK) model of the same types of wood.
6. Chapter 6 describes viscoelastic behaviour of the wood in water vapour sorption process using a Kelvin-Voigt (K-V) model (i.e. relaxation limited kinetics). Both PEK and K-V models are new approaches to explain the sorption phenomenon in wood cell walls at different relative humidity (RH). While the PEK model has been sometimes used for plant fibre sorption studies for nearly a decade. Its adoption to describe sorption phenomena with wood is very recent.
7. Chapter 7 describes the effect of isotherm temperatures on sorption properties of *Acacia mangium* and *Endospermum malaccense.* This data is further analysed to determine activation energies, entropies and Gibbs free energies of the sorption kinetics.
8. Chapter 8 describes general outcomes, the link between sorption hysteresis and kinetics and the plan of future study based upon consideration of polymer relaxation processes in glassy solids.

Throughout the thesis, each experimental chapter will cover the introduction, materials and methods, results and discussion and conclusions.

1.2 Aims of the study

Although the water vapour sorption behaviour of lignocellulosic and cellulosic materials has been studied for over a century, there is still much that is not understood about this phenomenon. The aim of this work was to further our understanding of the phenomenon of the water sorption of wood. This was driven by a realisation that although many models existed in the wood science literature, there was actually no satisfactory explanation as to why hysteresis occurred.

The objectives of this study were:

1. To gain an understanding of the property of sorption isotherm and the sorption hysteresis phenomenon in wood and thermally modified wood.
2. To gain an understanding of the property of sorption kinetics using the parallel exponential kinetics (PEK) model and the link with sorption hysteresis.
3. To examine the applicability of the Kelvin-Voigt viscoelasticity model for interpreting PEK data.
4. To determine effect of different isotherm temperatures on sorption kinetics properties and to calculate the activation energies, entropies and Gibbs free energy from this data.
5. To examine whether there may be a link between sorption hysteresis and kinetics

1.3 The Structure of Wood

Wood is a complex material and when considering the sorption properties of wood, it is necessary to take this complexity into account. In this respect it is important to note that the sorption studies undertaken in this work were on cell wall material and that the conclusions drawn may not be applicable to wood of larger dimension.

Wood is a natural material, and as such it exhibits great variability in its properties, it is cellular in structure, anisotropic and non-homogeneous. Wood is obtained from two broad categories of trees known commercially as softwoods and hardwoods. Softwoods are those woods that come from gymnosperms (spore-bearing plants with naked seeds), and hardwoods are woods that come from angiosperms (flowering plants with covered seeds). The wood of softwoods is more uniform than hardwoods which are easier to distinguish from one another visually. Hardwoods and softwoods differ in terms of the types of trees from which they are obtained, but they also differ in terms of their component cells (Figure 1.1). Due to their more complex structure, hardwoods are much more variable in their permeability and capillary behaviour (Siau 1995). The types of cells, their relative numbers and their arrangement are different, the fundamental difference being that hardwoods contain a type of cell called a vessel element which does not exist in softwoods (Table 1.1). It should be noted that not all softwoods are soft and not all hardwoods are hard. Some softwoods produce wood that is harder and denser than wood produced by some hardwoods (e.g. balsa wood is a hardwood). There are more hardwood species which cover a greater ecological diversity including

tropical and temperate regions. However softwoods such as coniferous species of the boreal forests cover a greater geographical area and represent a greater population of forest biomass.

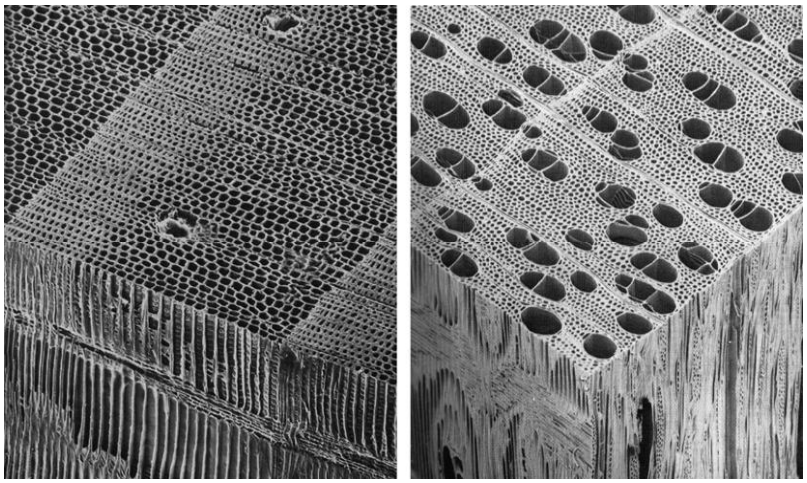
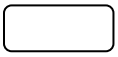
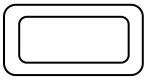
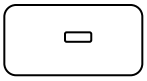
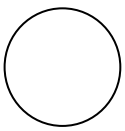


Figure 1.1 An example of the different structures of softwoods (Norway spruce) and hardwoods (birch) (Côté *et al.* 1979).

Table 1.1 Functions and wall thicknesses of the various types of cell found in softwoods and hardwoods (Dinwoodie 2000).

Cells	Softwood	Hardwood	Function	Wall thickness
Parenchyma	√	√	Storage	
Tracheids	√	√	Support, Conduction	
Fibres		√	Support	
Vessels (pores)		√	Conduction	

1.3.1 Growth rings

For most species in temperate climates, where there are clear seasons, the difference between wood that is formed early in a growing season and that formed later is sufficient to produce well-defined annual growth rings (Figure 1.2). The age of a tree at the stump may often be determined by the counting of these rings. Wood grown in a temperate climate nearly always produces one growth ring each year. Typically, a growth ring consists of two distinct parts (i.e. earlywood and latewood). However, if the growth in diameter of the trunk is interrupted, by drought or defoliation by insects for example, more than one ring may be formed in the same season. In tropical climates where there is often no seasonal difference, growth rings are likely to be indistinct or absent.

1.3.2 Heartwood

Heartwood is wood that has become more resistant to decay as a result of deposition of chemical substances or extractives (a genetically programmed process). Once heartwood formation is complete, the heartwood is dead. Usually heartwood looks different; in that case it can be seen on a cross-section, usually following the growth rings in shape. Heartwood may (or may not) be much darker than sapwood (Figure 1.2). It may (or may not) be sharply distinct from the sapwood. It can be distinguished using an iodine test for starch, which is only present in the live parenchymatic tissue of sapwood.

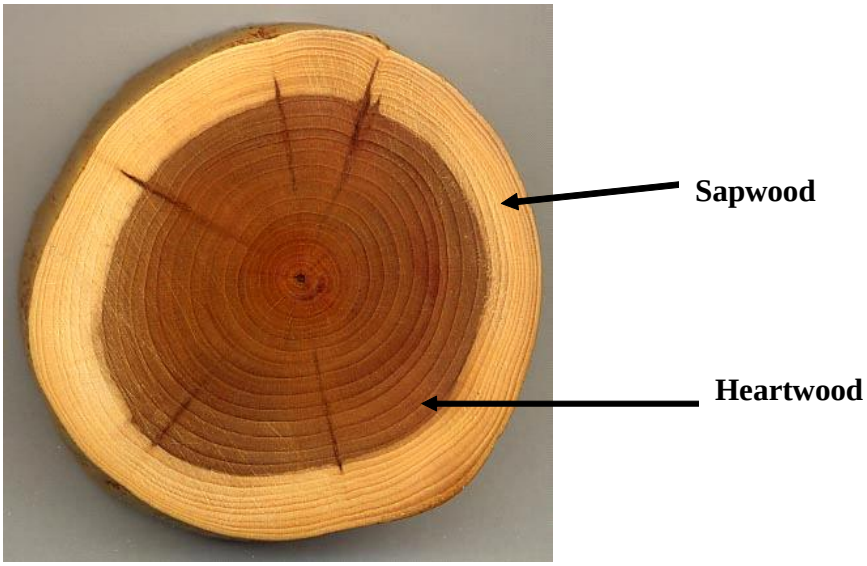


Figure 1.2 A cross section of a yew tree trunk showing the sapwood and heartwood.

1.3.2 Sapwood

Sapwood is the younger, outermost wood; its principal functions are to conduct water from the roots to the foliage. In sapwood, only the parenchymatic tissue and epithelial cells are alive and the other cells have a purely conduction or structural role. There is no definite relation between the annual rings of growth and the amount of sapwood, although sapwood width may correlate with the water demand from the foliage. Within the same species, the cross-sectional area of the sapwood is very roughly proportional to the size of the crown of the tree. As the tree gets larger, the sapwood must necessarily become thinner or increase materially in volume (Figure 1.2). Sapwood forms a greater proportion of the upper portion of the trunk of a tree than near the base, because the age and the diameter of the upper sections are less.

1.4 Softwood and Hardwood

1.4.1 Softwood

Softwood (the secondary xylem of gymnosperms) is composed of relatively few cell types; longitudinal tracheids, parenchyma, and epithelial cells. Softwoods are characterized by their simple anatomy, which consist mainly of longitudinal fibre tracheids (approximately 90-95 % by volume) (Fengel and Wegener 1989) (Figure 1.3). The tracheids or fibres are of dimensions between 2.5 – 7 mm long and 25 – 60 μm wide. The tracheids are used to move fluids throughout the living tree, hence the large open tube structure and the prominent pits to conduct fluids through the tree (Figure 1.3).

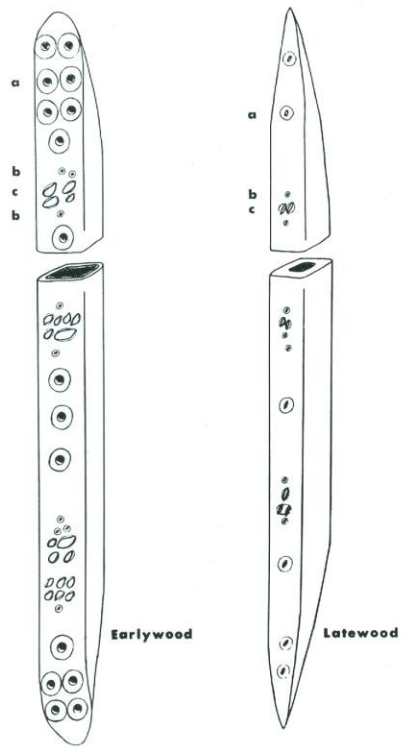


Figure 1.3 Radial surfaces of earlywood (left) and latewood (right) tracheids: (a) intertracheids bordered pits; (b) bordered pits to ray tracheids; (c) pinoid pits to ray parenchyma (Siau 1995).

Parenchyma cells, 5 – 10%, by volume and resin (epithelial) cells, 0.5 - 1.0% make up the remaining anatomy. The ray cells are radially arranged parenchyma cells and tracheids in softwoods that have storage function and frequently contain extractives (i.e. non-structural) material such as starch, fat, oils etc. The shape and size of rays vary significantly between species and are often used as a diagnostic feature in the microscopic identification of wood. Resin canals or ducts are tube-like voids that are both longitudinally and radially oriented throughout the xylem of some softwoods. Traumatic resin canals can be caused by wind, frost, insect or fungal attack and mechanical damage to the cambium caused by thinning and pruning operations or by animals. These, tend to develop in the weaker earlywood and to form an arc within the growth ring.

1.4.2 Hardwood

Hardwoods have a much more complex structure than softwoods. Hardwoods contain vessel elements (or pores), fibre tracheids, libriform fibres, and parenchyma cells which are arranged longitudinally and horizontally (Figure 1.4). The wood consists of 36-70% fibres, 20-55% vessel elements, 6-20% ray cells, with approximately 2% parenchyma cells by volume. Fibres are elongated cells with closed pointed ends and commonly have thick walls. The lengths range from 0.64 mm to 3 mm (Panshin and De Zeeuw 1980). Fibres provide mechanical support and the vessels are the main channel of fluid transportation. Hardwood fibres, because of the existence of vessels, occupy a proportionally smaller volume of wood tissue than softwood fibres do. Vessels are capillary tubes arranged vertically along the axis of the tree and are very important for conducting sap or minerals from the roots to the crown. The end

walls of the individual cells are pierced to facilitate the passage of sap. The length and width of each vessel cell varies from 0.2 to 1.3 mm and from 20 to 330 µm, respectively. These long pipes range from a few cm to some m in length (Fengel and Wegener 1984). Two structural features of vessel elements are the perforation plates and pits. In hardwoods, there are two types of vessel distribution; diffuse-porous and ring porous. Most of the hardwood species of the tropical forest are diffuse-porous characterized by the small differences in the diameter and the number of vessels over the whole growth ring. Ring porous wood, such as oak and elm, contain large vessels in the early wood and narrow vessels in the latewood with an abrupt size change (Desch 1973). The parenchyma-cell content of hardwoods is, on the average, much greater than that of softwoods.

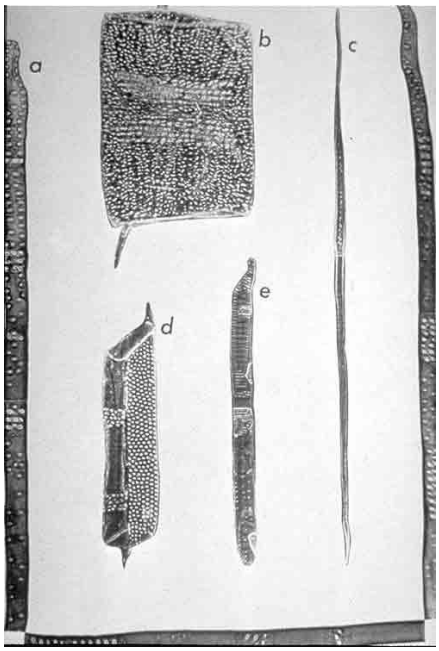


Figure 1.4 This diagram shows some of the cell types in softwoods and hardwoods. The long cell (a) is called a longitudinal tracheid of softwood. In hardwoods, more cell types are found, vessel element (b) is earlywood and (d) is latewood (c) Represents a hardwood fibre, while (e) is a hardwood tracheid (Côté *et al.* 1979).

1.5 The microfibril

The microfibril is the smallest structural element of the cell wall, and is reported to have a diameter of 3.5 nm (Mühlethaler 1960). The constituent in the microfibril structure is cellulose in a crystalline state. By analogy with composite theory, the microfibril can be considered as the fibre reinforcing element, while the 'matrix' comprises the hemicelluloses, lignin and cellulose present in a non-crystalline state (Figure 1.5). Siau (1995) noted that only the amorphous regions are accessible to bound water which can be sorbed on the hydroxyl groups, forcing the microfibrils apart and swelling the wood. These amorphous regions are primarily associated with the matrix components of which amorphous cellulose may form a minor constituent.

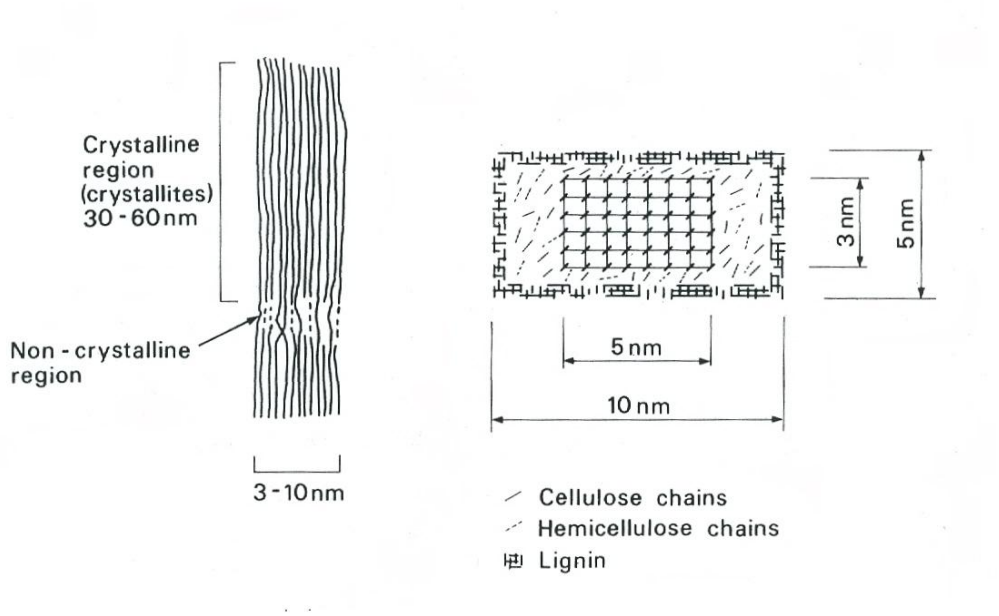


Figure 1.5 The microfibril in longitudinal view (a) and in cross section (b), showing the disposition of the various chemical constituents and the present of crystalline and non-crystalline region. (Desch and Dinwoodie 1996). This shows the series model for the longitudinal structure.

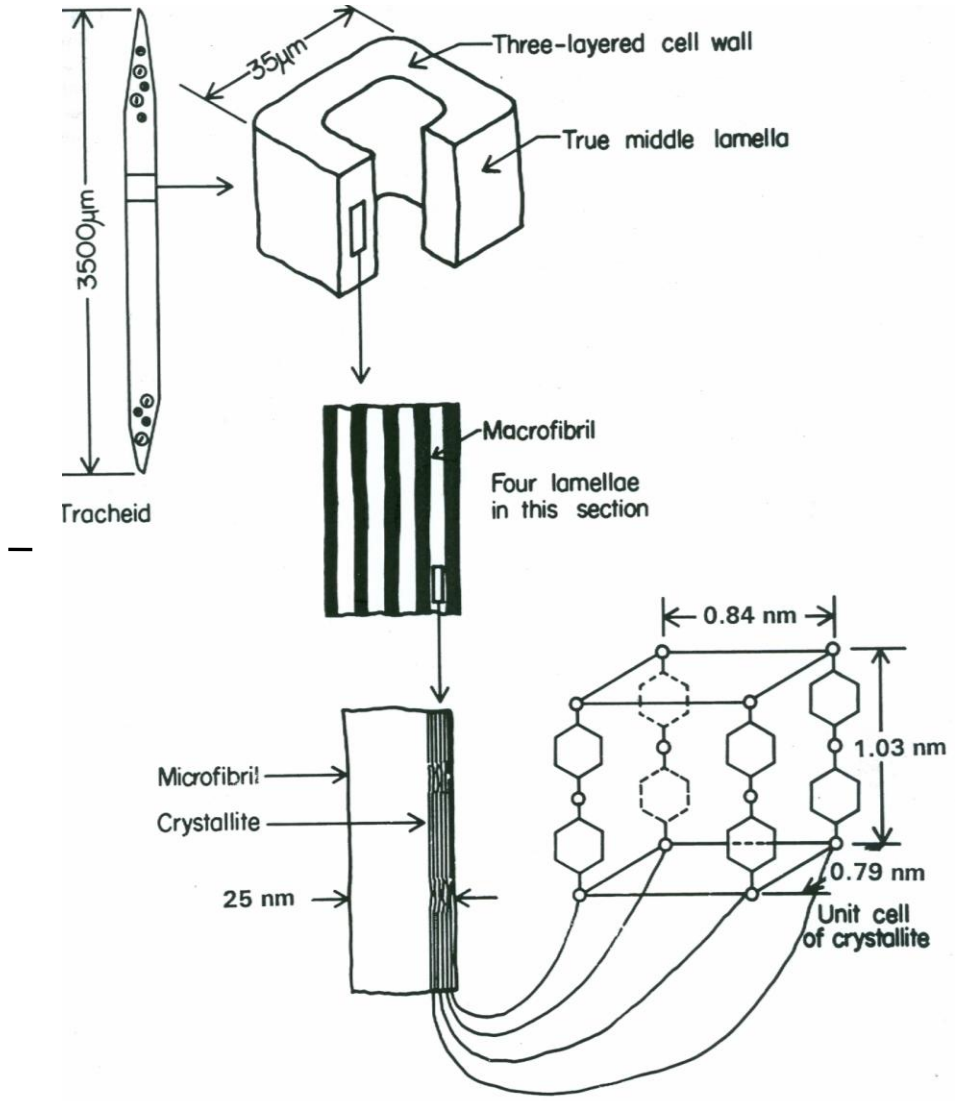


Figure 1.6 Relationship between the various elements making up the cell wall of coniferous wood (Siau 1995). The series model of the microfibril is shown.

1.6 The Cell wall of wood

Figure 1.6 shows an illustration of the relationship between the cellobiose segments of cellulose, the micelles including crystallites, the microfibrils,

macrofibrils, and the cell wall of coniferous wood (Siau 1995). The microfibrils are assumed to be aggregated into larger macrofibrils, which constitute lamella that are embedded in a lignin-hemicellulose matrix. This hierarchical process makes the various layer of the cell wall. The cell wall of wood is composed of a number of discernable layers (Fig. 1.7). These are divided into the primary (P) and secondary (S) layers; the secondary layer is further subdivided into S_1, S_2 and S_3 layers. The primary layer is the first to be laid down when the cell is formed and is composed of cellulose microfibrils, which have an essentially random orientation that allows for expansion of the cell to occur, as cell growth takes place. In the secondary wall layers, the microfibrils are closely packed and form lamellae within the cell wall. The secondary wall is laid down after cell elongation.

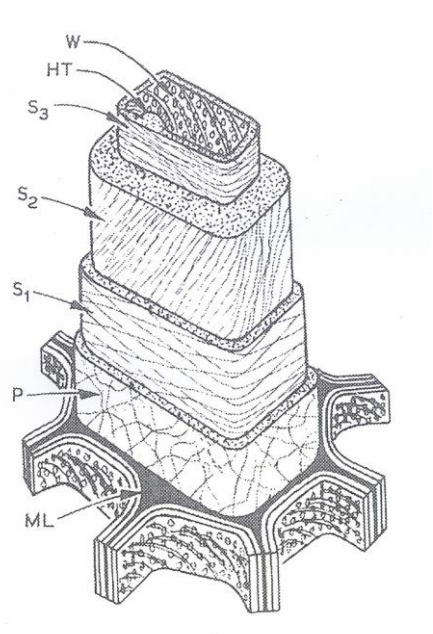


Figure 1.7 A schematic of the ultrastructure of the wood cell wall, showing the middle lamella, the main cell wall layers and the associated microfibril orientation (Haygreen and Bowyer 1982).

The outer layer of this wall, the S_1, is again thin and is characterized by having from four to six lamellae, the microfibrils of each alternating between a left and right hand spiral, both with a pitch to the longitudinal axis of from 50^o to 70^o depending on the species of wood. The middle layer of the secondary wall (S_2) is thick and is composed of 30-150 lamellae, the microfibrils of which all exhibit a similar orientation in a spiral with a pitch of 10^o to 30^o to the longitudinal axis. Three quarters of the volume of the cell wall is composed of the S_2 layer which consequently has a major influence on the behaviour of the wood (Dinwoodie 2000). The S_3 layer is very thin with only a few lamellae. It is characterized, as in the S_1 layer, by alternate lamellae possessing microfibrils orientated in opposite spirals with a pitch of $60\text{-}90^o$ (Table 1.2).

Table 1.2 Microfibrillar orientation and percentage thickness of the cell wall layers in spruce wood (*Picea abies*) (Dinwoodie 2000)

Cell wall layer	Approximate thickness [%]	Angle to longitudinal axis
P	3	random
S1	10	$50\text{-}70^o$
S2	85	$10\text{-}30^o$
S3	2	$60\text{-}90^o$

1.7 The chemical constituents of the cell wall of wood

1.7.1 Cellulose

Cellulose $(C_6H_{10}O_5)_n$ occurs in the form of long molecular chains, these having been built up within the cell wall from the glucose monomer ($C_6H_{12}O_6$). Generally, the proportion of chemical composition for wood is shown in Table 1.3. A number of

celluloses are closely associated via extensive H-bonding networks to form the microfibril, which is the primary reinforcing element in the cell wall. Cellulose is a linear (1→4)-linked glucan, consisting of β-D-glucopyranose residues in a chair conformation.

Table 1.3 Chemical composition of wood (Dinwoodie 2000)

Component	Mass		Polymeric state	Molecular derivatives	Function	Degree of polymerization (unit)
	Softwood (%)	Hardwood (%)				
Cellulose	42±2	45±2	Crystalline, highly oriented, large linear molecule	glucose	'fibre'	~ 10^4
Hemicelluloses	27±2	30±5	Semi-crystalline, smaller molecule	galactose mannose xylose	'matrix'	~300
Lignin	28±3	20±4	Amorphous, large 3-D molecule	phenylpropane		none
Extractives	3±2	5±4	Principally compounds soluble in organic solvents	terpenes, polyphenols, stilbenoids	decay resistance and others	none

Every glucose residue is inverted by 180^o with respect to its neighbour, and each has one primary and two secondary hydroxyl groups, as shown in Figure 1.8. Cellulose is partly crystalline in wood to the extent of 40% to 60% (Fengel and Wegener 1989). Cellulose is largely responsible for the tensile strength of wood and also contributes somewhat to the water adsorption of wood through its numerous hydroxyl groups, although many of these are located in the interior of the

microfibril and as a consequence are inaccessible to water. The location and amount of amorphous cellulose is still debated, but it seems reasonable to suppose that amorphous cellulose content is located on the exterior of the microfibril (parallel model). This content is accessible to water. Strictly speaking, this amorphous cellulose often possesses a degree of organization, and the term paracrystalline is often preferable.

1.7.2 Hemicelluloses

The hemicelluloses consist of a number of different types of sugar monomers, which vary with wood species. The monomer consists of six-carbon sugars (hexoses) including mannose, galactose and glucose, as well as, five-carbon sugars (pentoses) xylose and arabinose (Figure 1.9). Typical hemicellulose polymers include glucomannan, galactoglucomannan, arabinogalactan, glucuronoxylan and glucuronarabinoxylan. These structures are amorphous in nature. The total percentage of the hemicelluloses present in wood is larger in hardwoods compared to softwoods (Table 1.3). Hemicelluloses contain OH groups, and other functionalities, particularly carboxylic groups and have a degree of acetyl substitution, more so in hardwoods than softwoods.

1.7.3 Lignin

Lignin is a complex amorphous high molecular weight polymer built from phenyl propane units (Fig. 1.10). Composed of carbon, hydrogen, and oxygen, lignin is essentially phenolic in nature. Lignin occurs between individual cells and

within the cell walls. Between cells, it serves as a binding agent to hold the cells together. Lignin has a low concentration of OH groups compared to the polysaccharide components. Lignin is a glassy material with a glass transition temperature around 140 ^{o}C, although this is reduced when water is present (Hill 2006). A glass transition in the vicinity of 100 °C was identified for water-saturated lignin in wood by dynamic mechanical analysis (Salmén 1984). About 25% of the total lignin in wood is to be found in the middle lamella, an intercellular layer composed of lignin and pectin, together with the primary cell wall. The bulk of the lignin (about 75%) is present within the secondary cell wall, having been deposited during cell senescence.

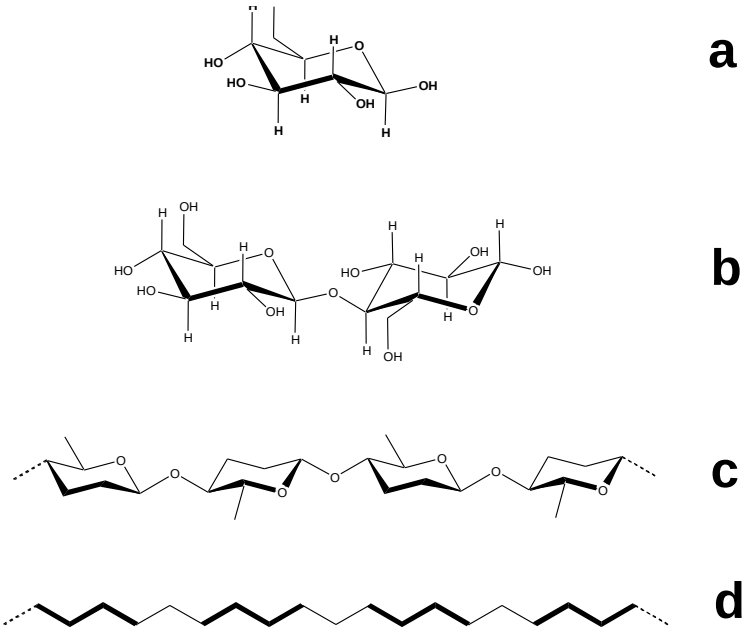


Figure 1.8 The molecular structure of β-D-glucopyranose (a), cellobiose-the repeat unit of cellulose (b) and the glucopyranose backbone of cellulose (c) and (d) a schematic of the linear arrangement of the glucopyranose units.

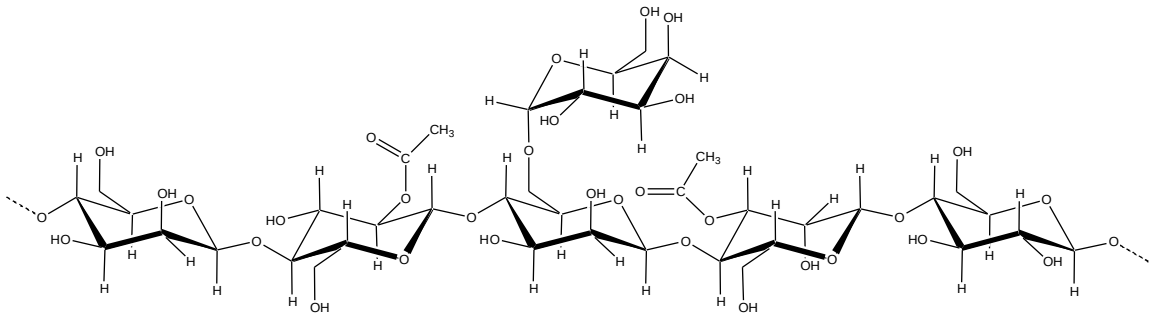


Figure 1.9 The molecular structure of a hemicellulose (*O*-acetylgalactoglucomannan).

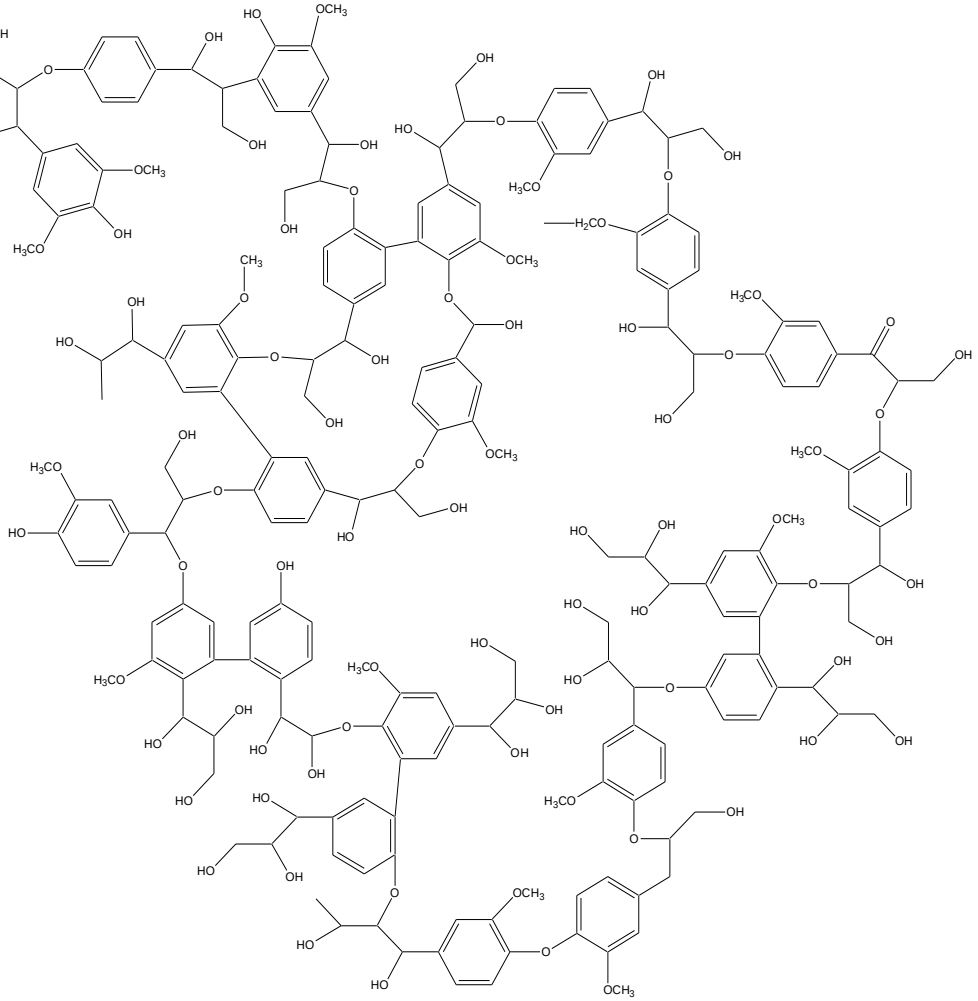


Figure 1.10 A representative molecular structure of a softwood lignin.

1.7.4 Extractives

Extractives are chemicals in the wood that can be removed using solvents. They are a group of cell wall chemicals mainly consisting of fats, fatty acids, fatty alcohols, phenols, terpenes, steroids, resin acids, rosin, waxes, and many other minor organic compounds. These chemicals exist as monomers, dimers and oligomers. Most of the extractives in both softwoods and hardwoods are located in the heartwood rather than sapwood (Hillis 1972), and some are responsible for the colour, smell, and durability of the wood. Table 1.3 shows the small amount of extractives present in temperate wood species (Dinwoodie 2000) but in tropical wood species it varies from 0.5% to around 20% by weight (Yamamoto and Hong 1988).

1.8 Tropical hardwoods species

Six tropical hardwoods species, *A. mangium* (*Acacia mangium*), *E. malaccense* (*Endospermum malaccense*), chengal (*Neobalanocarpus heimii*), kapur (*Dryobalanops* spp.), keruing (*Dipterocarpus* spp.) and ramin (*Gonystylus* spp.) heartwood were used in this study. *Acacia mangium* and *Endospermum malaccense* are among the 16 indigenous and exotic species that have been selected as plantation species in Malaysia based on their excellent growth performance, ease of management, and wide range of potential end uses (Rasip *et al.* 2004). On the other hand, chengal (*Neobalanocarpus heimii*), kapur (*Dryobalanops* spp.), keruing (*Dipterocarpus* spp.) and ramin (*Gonystylus* spp.) are the Malaysia's prime commercial wood species. The physical appearance (Figure 1.11) and the cellular

structure (Figure 1.12) of all the hardwoods were discussed separately. In general all the hardwoods are diffuse-porous which showed little change in the size and distribution of vessels across the growth ring.

1.8.1 *Acacia mangium*

Acacia is the standard Malaysian name for the wood of *Acacia mangium*. The wood is a medium hardwood, with a density ranging from 500-600 kg/m^3 air dried (Razali and Kuo 1991). Sapwood is pale-yellow to straw in colour and distinct from the heartwood which is light to dark-brown. Growth rings are absent. The vessels are moderately small with simple perforation. They are generally medium to moderate few, mostly solitary and in radial multiple of three (rarely more) and tyloses are absent. Wood parenchyma is present with paratracheal types. Ray tissue is moderately fine, barely visible or just visible to the naked eye on cross-section, not prominent on radial surface. The rays are mostly uniseriate (Sahri *et al*.1993).

1.8.2 *Endospermum malaccense*

Sesendok is the standard Malaysian name for the wood of *Endospermum malaccense.* The wood is a light hardwood, with a density ranging from 305-655 kg/m^3 air dried (Razali and Kuo 1991). The sapwood and heartwood are difficult to differentiate by colour. The wood is bright-yellow in colour with a subtle greenish tinge when freshly cut and changes to straw colour upon exposure. The vessels are moderately large in size and with simple perforation. They are few in number, some solitary, predominantly in radial pairs and multiples of 2 to 7 in a series and

occasional clusters in transverse section; tyloses are absent. Wood parenchyma is present with apotracheal types. Rays are fine but visible to the naked eye on cross-section (Nordahlia *et al.* 2010).

1.8.3 *Neobalanocarpus heimii*

Chengal is the standard Malaysian name for the wood of *Neobalanocarpus heimii*. The wood is a heavy hardwood, with a density ranging from 915-980 kg/m^3 air dried (Lopez 1983). Sapwood is pale-yellow in colour and distinct from the heartwood which is pale-brown when freshly cut and changes to dark-purple brown upon exposure. Growth rings are absent. The vessels are medium in size and with simple perforation. They are moderately numerous, mostly solitary, others in radial pairs and multiples of 2 to 4, evenly distributed without any clear arrangement and filled with tyloses. Wood parenchyma are abundant with both apotracheal and paratracheal types. Rays are moderately fine to medium-sized, visible to the naked eye on the cross section, but not conspicuous on the radial surface.

Figure 1.11 Illustration of the six Malaysian hardwoods (macro images).

1.8.4 *Dryobalanops* spp.

Kapur is the standard Malaysian name for the wood of *Dryobalanops* spp.. The wood is a medium hardwood, with a density ranging from 575 – 815 kg/m^3 air dried (Ser 1981). The sapwood is well defined; colour of heartwood rose-red or deep red; planed surfaces not particularly lustrous. Sapwood is light yellow-brown in colour and distinct from the heartwood which is deep-red when freshly cut and changes to red-brown upon exposure. Growth rings are absent but irregularly spaced, concentric layers or vertical canals may simulate growth rings. The vessels are medium-sized to moderately large and with simple perforation. They are evenly distributed, almost exclusively solitary and filled with abundant tyloses. Wood parenchyma is present with both apotracheal and paratracheal types. Rays are moderately fine to medium-sized and are visible to the naked eye on the end surface and tangential surface, but indistinct on radial surface.

1.8.5 *Dipterocarpus* spp.

Keruing is the standard Malaysian name for the wood of *Dipterocarpus* spp.. The wood is a medium hardwood, with an average density of 800 kg/m^3 air dried (Choo and Sim 1982). Sapwood is grey-brown in colour and distinct from the heartwood which is red-brown upon exposure. Growth rings are absent. The vessels are from moderately large to very large size and with simple perforation. They are exclusively solitary and evenly distributed with a tendency to be arranged in short oblique lines. Tyloses are usually very sparsely developed in most species. Wood

parenchyma is present with both apotracheal and paratracheal types. Rays are fine to medium in size and distinct to the naked eye.

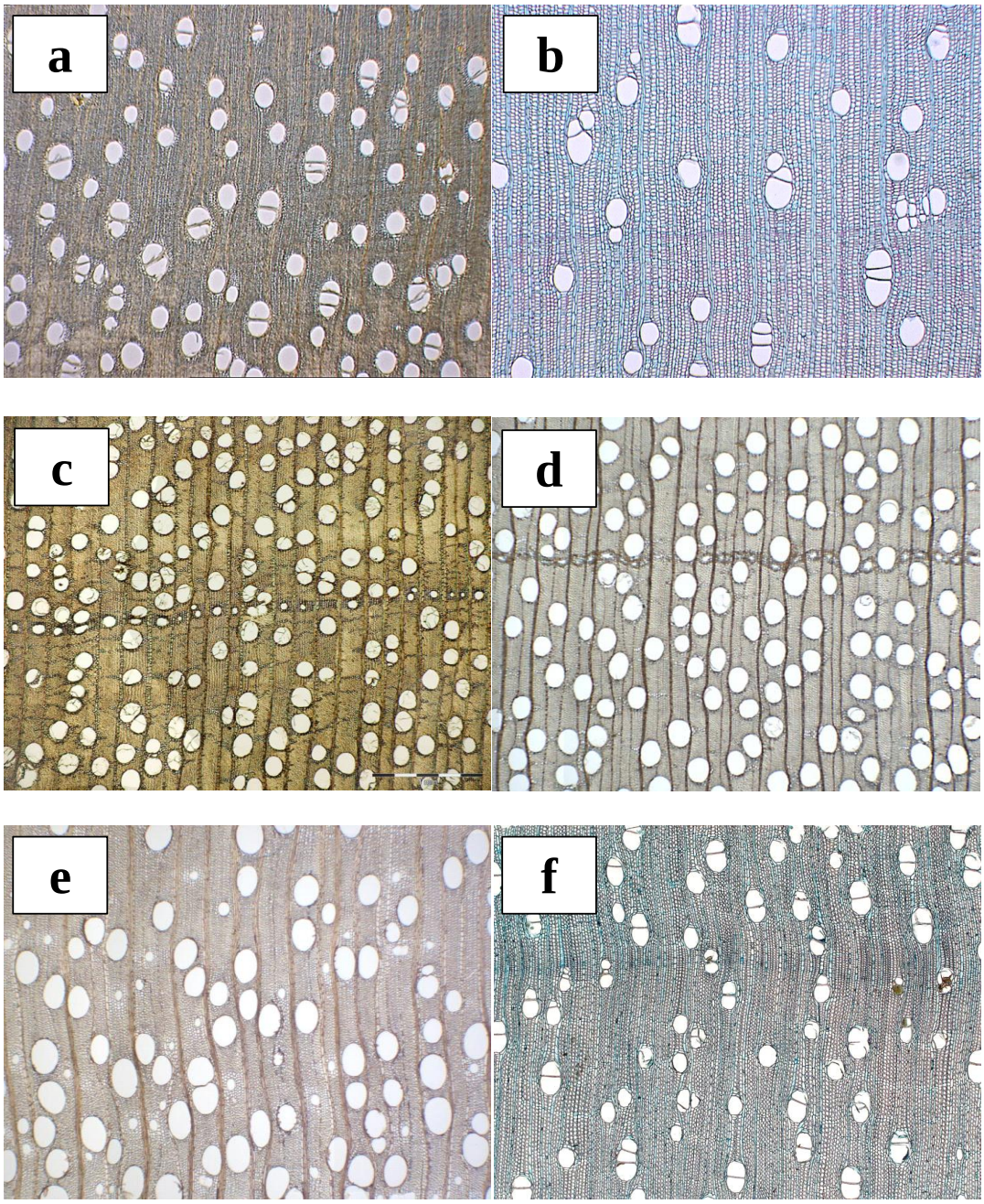


Figure 1.12 Tranverse section of (a) *A. mangium*, (b) *E. malaccense*, (c) *Neobalanocarpus heimii*, (d) *Dryobalanops* spp., (e) *Dipterocarpus* spp. and (f) *Gonystylus* spp. (Richter and Dallwitz 2000).

1.8.6 *Gonystylus* spp.

Ramin is the standard Malaysian name for the wood of *Gonystylus* spp.. The wood is a medium hardwood, with an average density of 550–570 kg/m^3 air dried (Sim 1983). The sapwood and heartwood are difficult to differentiate by colour. The wood is cream-white in colour and changes to pale-straw colour upon exposure. Growth rings are absent. The vessels are medium-sized, in multiples, commonly short (2–3 vessels) radial rows with simple perforation. They are few or moderately few in number, mostly as solitary, predominantly in radial pairs of up to 4 in a series and tyloses are absent. Wood parenchyma is present with paratracheal types. Rays are exclusively uniseriate.