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Tel: 03-89468851/89468854
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Email: penerbit@putra.upm.edu.my
Website: www.penerbit.upm.edu.my

ISBN: 9789673446797

INAUGURAL LECTURE series

Prof. Dr. Zaidon Ashaari

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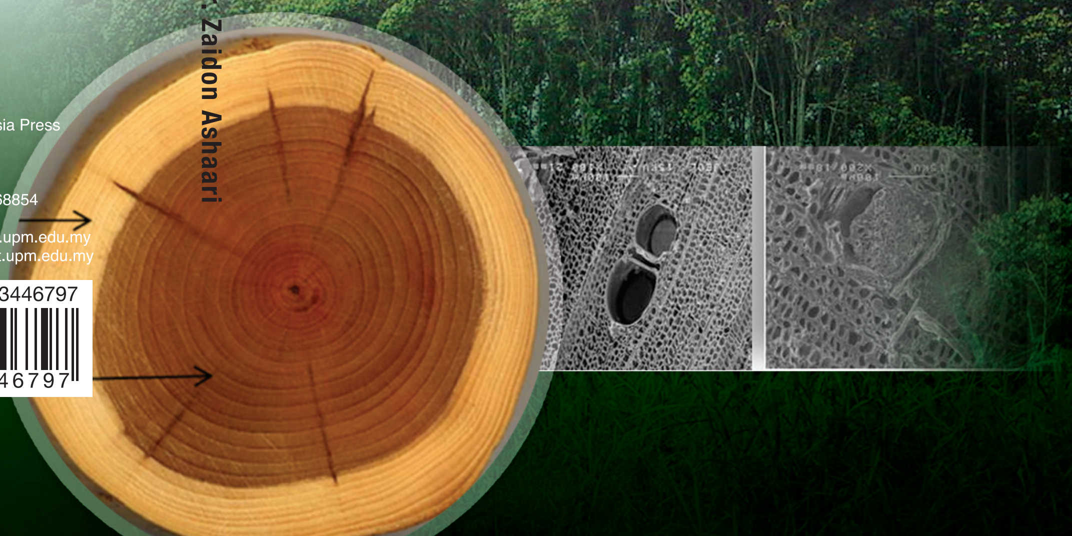

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PROFESSOR DR. ZAIDON ASHAARI

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10 FEBRUARY 2017

Dewan Kuliah Hutan
Fakulti Perhutanan
Universiti Putra Malaysia

Universiti Putra Malaysia Press
Serdang • 2017
http://www.penerbit.upm.edu.my

Cetakan Pertama 2017

Penerbit UPM adalah anggota Persatuan Penerbit Buku Malaysia (MABOPA)
No. Ahli: 9802

ISBN 978-967-344-679-7

Reka letak teks : Sahariah Abdol Rahim @ Ibrahim
Reka bentuk kulit : Md Fairus Ahmad

Reka bentuk, reka letak dan dicetak oleh
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ABSTRACT

One of the greatest attributes of wood is that it is a renewable resource. It has been used for thousands of years as both fuel and construction material. The raw materials used in Malaysia's wood-based industries comprise mainly hardwood extracted from natural and plantation forests. Hardwood timbers are classified into three categories, heavy hardwoods (HHW), medium hardwoods (MHW) and light hardwoods (LHW). The classification of the three hardwood categories is based largely on the average density of the timbers.

The timber industry is one of the major contributors to the Malaysian economy, contributing up to 2.7 per cent of the country's export earnings. The timber and timber products category commodity exports was the third most important after palm oil and rubber in 2014. The export of timber and timber products in 2015 was valued at RM21.14 billion and the government expects the industry to contribute RM53 billion to the country's export earnings by 2020. In order to ensure that the projected goal is achieved, an adequate and sustained supply of wood raw material is important for further development of the timber industry. Further, the timber industry needs to innovate and re-invent itself to stay competitive. It is expected that the future growth of the industry will be through higher productivity, innovation and technological breakthroughs. Innovation, in this context, refers to the successful exploitation of new ideas and designs that result in tangible products and services. Meanwhile, technology involves the application of knowledge, equipment, machines and processes, in translating innovations into newer, more sophisticated products for commercial gain. Hence, in order for the timber industry to remain relevant, it has to adopt new state-of-the-art technologies to overcome production bottlenecks and produce newer and more sophisticated products.

The wood-based products industry in Malaysia is expected to face the problem of inadequate supply of raw materials to sustain the growth of the industry in the future. Supply of raw materials from natural and plantation forests may not suffice and the industry will thus have to seek alternative raw materials to augment the diminishing supply of traditional commercial timbers. Through innovation and R&D activities, the inferior properties of low density wood, OPW and bamboo, which are normally used for traditional purposes, can be enhanced and become a source of alternative raw materials for the wood-based industries.

This lecture series is aimed at reviewing the importance of tropical wood, its classification, strength, durability and sustainability to meet the future demands of the wood-based industries. It further aims to highlight the research works carried out at the Faculty of Forestry, Universiti Putra Malaysia, on enhancing the properties of low density wood or underutilised timber species, particularly mahang (*Macarang* spp.), sesenduk (*Endospermum diadenum)*, jelutong (*Dyera costulata)* and oil palm wood (*Elaeis guineensis)*, so that they can be further utilised and made into higher value-added products.

INTRODUCTION

Wood is a porous and fibrous structural tissue found in the stems and roots of trees and other woody plants. Wood is sometimes defined as the hard fibrous substance consisting basically of the xylem that makes up the greater part beneath the bark of stems, branches and roots of trees and shrubs and, to a limited extent, in herbaceous plants (Wood, 2003). It is an organic material, a natural composite of cellulose fibre embedded in a matrix of lignin, which resists compression. In a living plant, it performs a mechanical function to enable the tree or woody plants to grow large or to stand up by themselves. It also conveys water and nutrients to the leaves, other growing tissues and the roots. Wood may also refer to other plant materials with comparable properties, and to material engineered from wood, or wood chips or fibre. One of the greatest attributes of wood is that it is a renewable resource, which has been used for thousands of years as both fuel and construction material.

The tree's growth process comprises of primary and secondary growth. Primary growth or apical growth occurs at the tips of branches and twigs, which eventually leads to increase in tree height. On the other hand, secondary growth or secondary thickening takes place at the cambium that finally results in an increase in the diameter or girth of a tree. During such growth processes, cell division at the apex and cambium results in the formation of woody tissue (Panshin & de Zeeuw, 1980). The woody tissue formed usually possesses bigger volume compared to the volume of the bark. This is attributed to the division of cells from the cambium towards the centre portion (pith), which is much greater than the cell division towards the bark. Woody tissue can be divided into two portions, namely, sapwood and heartwood (Figure 1). Sapwood, which is near to the bark, possesses less packed cells compared to the heartwood portion that is located near the pith (Jane *et al*., 1970). Heartwood is also normally darker than sapwood.

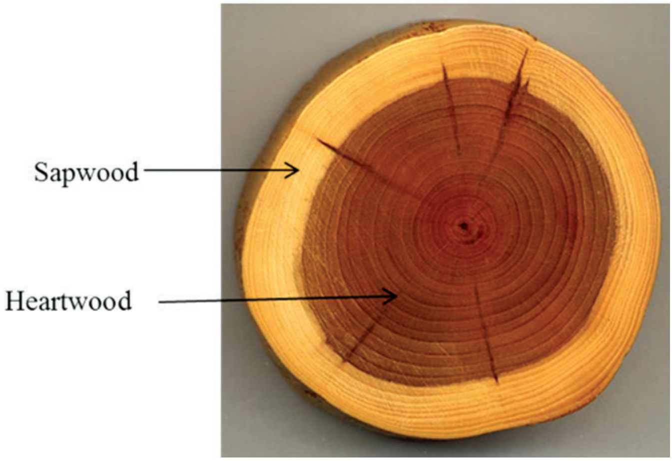


Figure 1 Sapwood and heartwood

Classification of Wood

Malaysian timbers are classified into four categories, , heavy hardwood (HHW), medium hardwood (MHW), light hardwood (LHW) and softwood. The distinction between hardwood and softwood is based on normal botanical convention. Hardwood is usually limited to flowering trees and shrubs and is characterised by wood containing water-conducting cells, vessel elements plus tightly-packed thick-walled fibre cells, which are lacking in the wood of conifers. Generally, the needle type leaves or cone-bearing trees, such as damar minyak (*Agathis borneensis),* podo (*Podocarpus* spp.) and sempilor (*Dacrydium* spp. and *Phyllocladus* spp.), are considered as softwood because the wood is composed essentially of water-conducting cells (tracheids) without wood fibre cells.

The weight and hardness of wood are attributed to the density of the cells, the amount of lignin in the cell walls and the percentage of tiny air spaces or pores within the cell walls. In fact, some slow-growing conifers such as pinyon pines and desert junipers (Juniperus) actually have wood with small, densely-packed tracheids that are harder and heavier than that of some of the so-called "medium hardwood". The classification of the three hardwood categories is based largely on the average density of the timbers at 15% moisture content (MC), as summarised in Table 1.

Table 1 Classification of Malaysian Hardwood

Classification	**Density Range, kgm^{-3} (at 15% MC)**
Heavy Hardwood	800-1120
Medium Hardwood	720-880
Light Hardwood	400-720

Source: MTIB (2008)

Density is defined as the mass per unit volume and is obtained by dividing the weight of a piece of wood (in kilogram) by its volume (in cubic meters). Thus, wood species having a density of less than 1000 kgm^{-3} (density of water) will float on the surface of water. The heaviest wood in the world is lignum vitae (*Guaicum officinale*, 1370 kgm^{-3}), which is also known as ironwood, that can sink in water. Meanwhile, the Tropical American balsa (*Ochroma pyramidale*) is one of the softest and lightest wood, with a density of only 170 kgm^{-3} (Armstrong, 1995). Density values are usually provided in a range because different portions of wood, especially between the heartwood and sapwood, exhibit different density values (Rowell, 1994). For example, merbau (*Intsia palembica*), which is classified into HHW, has a density range of 515-1040 kgm^{-3}, keruing (*Dipterocarpus spp.*), which is MHW, has a density range of 690-945 kgm^{-3} and sesenduk (*Endospermum diadenum*), LHW timber, a range of 305-644 kgm^{-3} (MTIB, 2008).

Strength and Durability Class

The strength grouping of tropical hardwood timber can be classified into two, namely, strength groups (SG) A to D, which is based solely on compression strength parallel to the grain (Table 2, MTIB, 2008) or SG 1 to 7, which corresponds to grade stresses (Table 3, MS544: Part 2: 2001). The strength of tropical hardwood is very much associated with their densities. Most of the HHW (density range within 800 – 1120 kgm^{-3}) belongs to the strength group A or group B. For instance, Balau, with a density range of 850–1155 kgm^{-3}, belongs to SG A, while Red Balau (800–880 kgm^{-3}) falls into SG B. Most timbers from MHW belong to either SG B or C and are occasionally in SG A. Timbers in class LHW are normally in the strength groups C and D, with those having density of below 500 kgm^{-3} in the strength group D. Examples of the low density wood in this category are jelutong (*Dyera costulata*), mahang (*Macaranga* sp.) and sesenduk *(Endospermum diadenum*).

Table 2 Strength Grouping Table

Strength group	Compression strength parallel to the grain (Nmm^{-2})
A	Greater than 55.2; extremely strong
B	41.4-55.2; very strong
C	27.6 - 41.4; moderately strong
D	Less than 27.6: weakest

Note: Determined using the test procedure described in ASTM D143-52 (1967).

Table 3 Dry grade stress for various strength groups of timber (Nmm^{-2})

Strength group	Bending (MOR)	Tension parallel to grain	Compression		Modulus of elasticity (MOE)
			Parallel to grain	Perpendicular to grain	
SG1	26.5	15.9	22.5	3.74	18800
SG2	18.3	11	18.5	3.05	16800
SG3	15.9	9.5	14.1	2.09	14300
SG4	13.2	7.9	11.1	1.65	11000
SG5	9.5	5.7	8.5	1.14	9100
SG6	8.9	5.3	6.9	1.02	7300
SG7	6.5	3.9	5.4	0.62	6600

Note: The grade stress is adopted from dry standard structural grade in MS 544 Part 2 (2001)

Durability refers to the natural durability of the heartwood. The natural durability of timber may be defined as the inherent resistance of heartwood timber to attacks by wood destroying organisms, such as wood decaying fungi and wood destroying insects. Sapwood timber of all species has very poor durability. Although no native wood is entirely immune to the attacks of such organisms, a number possess superior resistance. Wood is more resistant towards deterioration by microorganisms than most other plant tissues. Some of the natural resistance of woody tissues is partly due to the characteristics of the principal cell wall constituents. Nonetheless, the main reason for the natural durability of some species of wood is the presence of toxic substances in the heartwood. Sapwood is non-durable because it contains living cells that store food materials such as starch and sugar, which are the sources of food for some biodeterioration agents. In Malaysia, natural durability is measured based on a wood's performance in 'graveyard testing'. This method of testing entails the monitoring of test-sticks (heartwood) measuring 50 mm x 50 mm x 600 mm buried in a test ground. The number of years that the test-sticks can last under specific conditions is the basis of the natural durability grouping (Table 4). Another method of testing the natural durability of timber is by accelerated laboratory exposure to deteriorating fungi (Findlay, 1985). This testing method involves exposing blocks of wood (20 x 20 x 20 mm^3) to deteriorating fungus and the weight loss of the samples calculated after 16 weeks of incubation. For this test, four classes of degradations are used.

Table 4 Natural durability classes for tropical and temperate exposure and laboratory exposure (Findlay, 1985)

Classification	Service life under		
	Tropical conditions (years)	**temperate conditions (years)**	**Laboratory conditions[a] (% wt. loss)**
Very durable	> 10	> 25	< 1
Durable	5 - 10	15 - 25	1 - 5
Moderately durable	2 - 5	10 - 15	5-10
Non-durable	< 2	<5	>10

a16 weeks incubation at 220C: test fungi listed in Eaton and Hale (1993)

Among the very durable heavy hardwoods are balau (*Shorea* spp.), belian (*Eusideroxylon zwageri*), giam (*Hopea spp.*) and malagangai *(Eusideroxylon malagangai*). Majority of the light hardwood falls in either the moderately durable or non-durable groups. Among the non-durable commercial timber species are light red meranti (*Shorea* spp.), rubberwood (*Hevea brasiliensis*), jelutong (*Dyera costulata*), sesenduk (*Endospermum diadenum*) and mahang (*Macaranga sp.*), whereby their applications are limited to indoors or in an environment where they will not be in contact with soil or moist conditions. Plantation species (10-yr-old), *Acacia mangium*, *Acacia crassicarpa, Acacia auriculiformis, Gmelina arborea* (yamane) and *azdirachta excelsa* (sentang*)* are also found to be non-durable. A laboratory exposure test showed that these timber species exhibited more than 10% weight loss when subjected to white rot fungus as compared to the *Neobalanocarpus hemii* (chengal), a very durable hardwood, with a weight loss value of 2.16% (Zaidon *et al.,* 2002).

SCENARIO OF FORESTRY SECTOR IN MALAYSIA

Malaysia is one of the world's largest exporters of tropical timber and timber products, and one of the ten largest exporters of furniture (i.e., second in Asia), with over 160 export destinations (MTIB, 2015). Malaysia has also established itself as both a major producer and exporter of sawn timber, panel products (plywood, medium density fibreboard or MDF and particleboard), flooring, doors and other joinery products. In 2014, there were more than 4,000 processing mills in the timber industry (Table 5). Most of these mills were involved in furniture and woodworking manufacturing (2,152) and sawmilling (1,019) and a majority of them were located in Peninsular Malaysia.

Table 5 Licensed Mills in the Malaysian Timber Industry, 2013-2014

Mill Types	Peninsular Malaysia	Sabah	Sarawak	MALAYSIA
Sawn timber	694	154	171	1,019
Plywood/ Veneer/ Blockboard	40	49	66	155
Mouldings	158	122	38	318
Particleboard/ Chipboard	22	3	1	26
Pulp and paper	-	1	-	1
Furniture and woodworking	1,295	440	417	2,152
Laminated board	34	-	12	46
Woodchips	8	5	6	19
MDF	9	2	3	14
Others	266	95	131	492
Grand total	2526	871	845	4242

Sources: FDPM (2014), SFD (2013), STIDC (2013)

The timber industry is one of the major contributors to Malaysia's export earnings, by up to 2.7 per cent. 'Timber and timber products' category of exports was the third most important commodity after palm oil and rubber, in 2014 (DOS, 2015; MTIB, 2015). The export of timber and timber products in 2015 was valued at RM21.14 billion (Table 6), which was an increase of over three per cent from 2014. Wooden and rattan furniture has been the major export earner and accounted for 37% of the total wood commodity exports valued at RM8.6 billion.

Table 6 Production and Export Value of Selected Primary Products, 2015

Products	**Pen. Malaysia**		**Sabah**		**Sarawak**		**Malaysia**	
	Prod^n (mil m^3)	**Exp. (RM mil)**	**Prod^n (mil m^3)**	**Exp. (RM mil)**	**Prod^n (mil m^3)**	**Exp. (RM mil)**	**Prod^n (mil m^3)**	**Exp. (RM mil)**
Logs	0.0163	18.16	0.350	217	2.661	1,788	3.028	2,023 (9%)
Sawn timber	1.253	2,094	0.192	360.5	0.570	721	2.016	3,175 (14%)
Plywood	0.234	409.7	0.498	943.5	1.802	3,336	2.534	4,690 (21%)
Veneer	0.010	21.57	0.059	95.01	0.013	235.08	0.229	351.66 (2%)
Mouldings	0.225	709.82	0.0245	91.34	0.0133	30.78	0.263	831.93 (4%)
Chip/ particleboard/MDF	1.275	1,196	0.0053	4.660	0.252	304.10	1.532	1,505 (7%)
Wooden frame joinery/ furniture	n.a	8,315	n.a	4,506	n.a	2,041	n.a	8,564 (39%)
Other products	n.a	636	n.a	187.6	n.a	180.4	n.a.	1,004 (4%)
Grand Total	**n.a**	**13,400**	**n.a**	**1,944**	**n.a**	**6,800**	**n.a**	**22,145 (100%)**

Sources: DOS (2015) and MTIB (2015).

About 80% of the furniture exports were manufactured from Malaysian rubberwood. Ranked as the 8th largest exporter of furniture in the world, Malaysia exports around 80% of its production and large markets are US, Japan and Australia. Plywood and veneer products were the second largest foreign exchange earners (21%) for the timber industry in 2015. The export value of plywood and veneer products amounted to RM4.7 billion in the same year.

The government expects the timber industry in Malaysia to contribute RM53 billion to the country's export earnings by 2020 (NATIP, 2009). This is more than twice the present revenue. In order to ensure that the projected goal of RM 53 billion can be achieved, an adequate and sustained supply of wood raw material, for further development of the timber industry, is essential.

SUSTAINABILITY OF WOOD SUPPLY

The major sources of the raw materials for the industry have been from natural forests, state land forests, alienated lands and rubber replanting programmes. Under the Third Industrial Master Plan (IMP3, 2006-2020), the annual exports of the timber industry have been targeted to reach RM53 billion by 2020. Thus, it is anticipated that there will be a shortfall of raw materials due to the reduced opening of state land forests and alienated lands for development. This situation must be addressed urgently by implementing appropriate policy measures. One solution to this problem is to encourage outward investments in the production of logs and semi-finished components in timber resources-rich countries, to supplement the insufficient supply of local raw materials to the timber industry.

The crucial roles of forests are many, one of which is as a production unit providing for the long-term availability of forest resources, including the long-term supply of timber. Currently, the total area of forests in Malaysia is estimated to be 19.12 million ha or 58.1% of the total land area, with the percentage of the forested lands being higher in the states of Sabah and Sarawak than in Peninsular Malaysia (Table 7).

The key to the success of the timber industry is the readily available supply of raw materials. However, as shown in Table 8, the trend of log production is declining. The government has thus introduced various measures to meet the needs of the industry. These measures include enhancing Sustainable Forest Management (SFM) measures, as well as the Forest Plantations Programme (FPP), to ensure the sustainable supply of raw materials. For instance, in Malaysia, approximately 0.94 mil hectares of forest plantation area had been established as of December 2014 (FDPM, 2014), and planted with species such as acacia, teak, rubber, sentang and pine, among others. The establishment of such commercial plantations in Malaysia, through the Compensatory Forest Plantation Programme (CFPP), was launched in 1982. These plantations are filled with fast growing species, such as *Acacia mangium*, *Paraserianthes falcataria* and *Gmelina arborea*, which are harvested within a short rotation cycle of 15 years. In 2006, the Malaysia Timber Industry Board (MTIB) set up Forest Plantation Development Sdn. Bhd. to establish large scale commercial plantations in Malaysia. The eight recommended species for the project were *Acacia mangium* (acacia), *Hevea brasiliensis* (rubber), *Khaya ivorensis* (African mahagony), *Tectona grandis* (teak), *Neolamarckia cadamba* (kelampayan), *Azadirachta excelsa* (sentang), *Octomeles sumatrana* (binuang) and *Paraserianthes falcataria* (batai). These are all fast growing multipurpose trees comprised of both exotic and local species (MTC, 2015).

Table 7 Total area covered by forest in Malaysia (2013-2014, million ha)

Region	Land Area	Natural Forest			Plantation Forest	Total Forested Land	% Total of Forested Land
		Dry Inland Forest	Swamp forest	Mangrove Forest			
Peninsular Malaysia	13.17	4.19	0.26	0.11	0.39	4.93	44.0
Sabah	7.36	3.50	0.12	0.28	0.22	4.11	55.8
Sarawak	12.40	9.35	0.61	0.070	0.33	10.08	81.2
Malaysia	32.93	17.04	0.99	0.46	0.94	19.12	58.1

Sources: FDPM (2014), SFD (2014) and STIDC (2013)

The industry is also encouraged to utilise wood residues, low density wood, oil palm wood and biomass and also to maximise the wood recovery rates through improvements in the processing technology, to meet the needs of the industry.

Table 8 Production of logs in Peninsular Malaysia ($000m^3$ in 2005 and 2014)

Timber groups	2005	2014	Change in production (%)
HHW	414	313	-2.29
MHW	1,325	1,429	2.36
LHW	2,664	2,371	-6.65
Softwood	1.72	1.04	-0.02
Total	**4,405**	**4,114**	**-6.6**

Source: FDPM (2014)

LOW DENSITY AND UNDERUTILISED WOOD SPECIES

Light hard woods, especially those with the density value of below 500 kgm^{-3}, are normally underutilised due to their poor strength and non-durability, which limit their final applications. Commonly, light hard wood is susceptible to biological agents and has low strength, ranging from strength groups (SG) 5 to SG 7. This lecture series is thus aimed at discussing ways to enhance the properties of low density wood species, such as mahang, jelutong, sesenduk and oil palm wood, so that they can be alternative materials to commercial timbers, which are now depleting in supply, to meet the needs of the industry. The physical and mechanical properties of these species are summarised in Table 9.

Table 9. Physical and mechanical properties of selected low density tropical hardwood and oil palm wood

Properties	Sesenduk	Jelutong	Mahang	Oil palm wood (OPW)		
				Outer	Middle	Centre
Physical properties						
Density, kg/m3	270-500	420-500	270-495	362	254	196
AD shrinkage (T) %	1.3	2.0	n.a	n.a	n.a	n.a
Total shrinkage (T)%	5.45	5.5	7	n.a	n.a	n.a
AD shrinkage (R) %	1.2	0.8	n.a	n.a	n.a	n.a
Total Shrinkage (R)%	2.71	2.3	3	n.a	n.a	n.a
Vol. Shrinkage %	n.a	6.2	n.a	22.6	50,1	67.8
Mechanical properties						
MOR, N/mm2	39	50	42-50	29.54	12.90	6.69
MOE, N/mm2	8500	8100	4940-6728	300	114	62.80
Comp. parallel to grain, N/mm2	20.80	27.0	19-27	14.57	5.33	4.06
Shear, N/mm2	5.40	5.8	5.7-6.6	3.2	1.0	1.0
Hardness, kN	1.18	1.74	1.03	1.0-11.8	0.67-5.3	0.3-4.8

Source: Mohd Hamami et al. (2012); n.a. = not available

Mahang *(Macaranga* spp.)

Macaranga spp. is a small tree which can grow up to 25 m in height and 30 cm diameter breast height (DBH) (Figure 2). This is an early successional tree that grows mainly in swamps, up to 100 m in altitude. *Macaranga* spp. comprises some 250 species, whereby about 30 appear in tropical Africa and Madagascar, and the rest in tropical Asia (from India to Indo-China, China, Taiwan and the Ryukyu Island), throughout the Malesian region, northern Australia and the Pacific, east to Fiji. The main centre of its diversity is found within Malesia, where some 160 species grow, with an exceptionally high number of endemic species found in Borneo and New Guinea (Sosef *et al.,* 1998).

Figure 2 Mahang tree (left); texture and colour of the mahang wood (right)

Macaranga timber has a density ranging from 270 to 495 kgm^{-3} (Table 9) and its heartwood is pale yellow-brown to pale brown or grey-brown, sometimes with a pinkish tinge, and not clearly differentiated from the sapwood. The wood is somewhat fibrous, soft to moderately and fairly weak, and easy to work on. Shrinkage is moderate, with a total shrinkage of 7.0% and 3.0% in the tangential and radial directions, respectively. In static bending, the MOR ranges from 42-50 Nmm^{-2} and the MOE is between 4940-6728 Nmm^{-2}. Its compression strength is between 19- 27 Nmm^{-2}, shear 5.7- 6.6 Nmm^{-2} and hardness is 1.03 kN. This wood is classified under SG 7 and is non-durable (MS, 2001; MTIB, 2008), but it is permeable to pressure treatment.

Mahang wood is traditionally used for temporary construction, especially for parts of native houses that are not in contact with the ground. It can also be used for light framing, interior trim, moulding, shingles, packing cases and match splints. In the Philippines, this wood is a favourite material for wooden shoes. *Macaranga* produces high-quality pulps and particleboards, cement-bonded boards and wood-wool boards. It is also suitable for the production of plywood, apart from being known as good fuel wood.

Sesenduk (*Endospermum* spp.)

Sesenduk belongs to the family *Euphorbiaceae*, which comprises 13 species that are widely distributed from Assam (India), throughout the mainland of South-East Asia and China, towards the Malesian archipelago, including Peninsular Malaysia, Sumatra, Borneo Island, the Philippines, northern Sulawesi, Moluccas and New Guinea, and further east towards Fiji and the south of northern Queensland. Almost all its species occur within the Malesian area. The three most widespread ones are *E. diadenum, E. moluccanum, and E. peltatum.* There is only one species (i.e., *E. diadenum*) found in Peninsular Malaysia (Figure 3), while *E. peltatum* is found in Sabah and Sarawak (Sosef *et al.,* 1998).

The density of this wood ranges from 270-500 kgm^{-3} (Table 9). The sapwood is not differentiated from the heartwood, which is bright yellow when fresh, often with a green tinge and darkens to light brown upon exposure. The grain is straight, interlocked or wavy, with a texture that is moderately coarse to coarse, but even (Figure 3). Slight checking may occur during drying, with a total shrinkage of 5.45% in the tangential direction and 2.71% in the radial direction (MTIB, 2008). The timber is not durable and very susceptible to fungal decay and insect attacks. It has good peeling properties and produces quality veneers without any pre-treatment, as well as good gluing, painting, screwing and nailing properties.

Figure 3 Sesenduk tree (left); the texture and colour of sesenduk wood (right)

The timber falls into SG 7, with a static bending MOR of 39 Nmm^{-2} and MOE of 8500 Nmm^{-2} (MS, 2001). The compression parallel to grain is 20.8 Nmm^{-2} with shear of 5.43 Nmm^{-2} and the hardness is 1.18 kN. Sesenduk timber is generally used for match boxes and splints, chopsticks, popsicle sticks, medical sticks (spatula), ice-cream spoons, toothpicks, carvings and handicrafts. The wood is non-durable when used in contact with the ground, hence, all the applications should avoid direct ground contact. It is also suitable for pattern making, drawing boards, pencil slats, blockboard trays, furniture parts, picture frames, plywood chests, packing cases and crates and buoys and floats. In addition, the wood can also be fabricated into laminated wood for panelling and moulding. The fibres are suitable for pulp, paper and fibre-board productions.

Jelutong (*Dyera costulata*)

Jelutong belongs to the family *Apocynaceae* (Figure 4). Jelutong trees can grow up to 80 m in height with diameters of up to 3 m, with clear and straight bole up to 30 m. Though the distribution of this species is commonly found in well drained virgin lowlands and hill forests in Malaysia, Indonesia and Thailand, it can also be found in regenerated logged over forests.

Figure 4 Jelutong tree (left); texture and colour of jelutong wood (right)

Jelutong has traditionally been overharvested, and is a threatened species in many areas. However, due to its quick growth and hardy survival, as well as strong replanting efforts, its extinction is unlikely. Furthermore, this species is now planted commercially for its timber in Malaysia. From 1920 to 1960, the white latex of the jelutong was actively collected as it was one of the main ingredients for chewing gum processing. The timber dries fairly fast with a total shrinkage of 5.5% and 2.3% in tangential and radial directions, respectively (MTIB, 2008). The timber is non-durable and classified into SG 6 to SG 7 (MS, 2001). The mean MOR for this timber is 50 Nmm^{-2} and MOE is 8,100 Nmm^{-2}. Compression parallel to the grain is Nmm^{-2}, shear is 5.8 Nmm^{-2} and hardness 1.74 kN. Jelutong is the preferred wood for manufacturing pencils and picture frames. This creamy white to pale straw coloured wood is also suitable for marquetry, carving, drawing boards, dowels, wooden toys, matchboxes and packing cases.

Oil Palm (*Elaeis guineensis* Jacq.)

The Oil palm tree belongs to the family *Palmae*. It occurs naturally in the tropical rain forests of West Africa, stretching from Senegal to Angola, and extending further along the Congo River. The oil palm was first introduced into Malaysia in 1870 through the Botanical Gardens, Singapore. Extensive cultivation was however not carried out until the 1960s. Today, the total area under oil palm cultivation in Malaysia is well over 5 million hectares, about 80% of which is in Peninsular Malaysia. Mature oil palm trees are usually felled after the age of 25 years (Figure 5), and this is either due to their decreasing yields or because they have grown too tall, causing difficulties in harvesting work. Oil palm stems are normally disposed off by either leaving them to rot or burning them in the field.

Figure 5 Mature oil palm trees

The oil palm, being a monocotyledon, has marked structural differences from tropical timbers. The most remarkable features of woody monocotyledons are that most of them achieve their stature without secondary thickening. Thus, unlike wood, the wood of oil palm consists of primary vascular bundles that are embedded in parenchymatous tissue. There is usually a very hard peripheral rind surrounding the soft central region. Nonetheless, the wood of oil palm (OPW) is not homogenous. Anatomically, the hard peripheral zone is composed of a narrow layer of parenchyma and congested vascular bundles that give rise to a sclerotic zone, which forms the main mechanical support to the palm stem (Figure 6). The central zone consists of larger and widely scattered vascular bundles that are embedded in the thin-walled parenchymatous tissue.

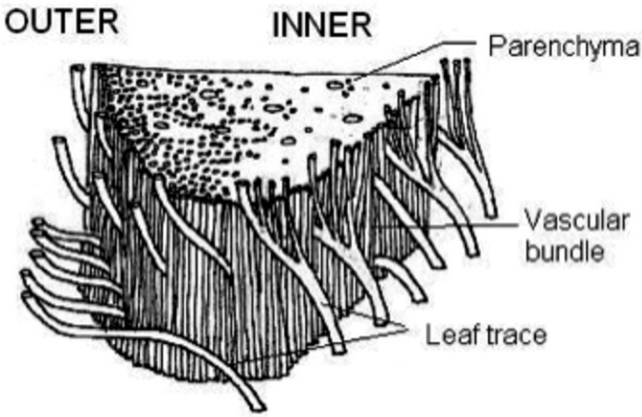


Figure 6 The structure of oil palm wood

OPW has great variation of density at different parts of the stem. Its density is low in the centre of the stem, but gradually increases toward the bark. The average density values range from 196-362 kgm^{-3} air dry (Table 9). The timber is very susceptible to fungal and insect attacks due to the presence of high sugar and starch contents. The stem is rather difficult to process, particularly at the region near the bark, due to the presence of silica in the cells. Meanwhile, the lumber of oil palm trunk is difficult to dry and it also suffers from various drying defects, including raised grain, warping and collapse. The total volumetric shrinkages recorded for oil palm wood were 22.6% at the outer layer, 50.1% at the middle and 67.8% at the inner core.

The high density variations within the oil palm stem have a significant effect on its strength properties (Bakar *et al.,* 2000). Table 9 shows the basic strength properties of oil palm wood which were tested at the outer, middle and central layers. The MOR was found to be in the range of 6.69-29.54 Nmm^{-2}, with 62.8-229.95

Nmm^{-2} for MOE, and the compression parallel to the grain between 4.06-14.57 Nmm^{-2} and a hardness of 0.3-11.8 kN.

Oil palm wood has potential to be used for various applications. With proper treatment, oil palm wood could be used for various light construction applications. Moreover, it can also be used as a core material for the production of block boards and plywood, which in turn, can be used as framing materials for the manufacture of upholstery furniture (Figure 7). Some selected materials from the stem may also be used to manufacture furniture. In particular, veneers that are obtained from the stem are used for manufacturing formed plywood for furniture components.

Figure 7 Oil palm veneers are used for plywood (left) and LVL (right) production

Apart from the uses mentioned above, the other possible usage of the oil palm stem is in the form of composite panel products, such as particleboards, wood-cement boards, gypsum-bonded particleboards and medium density fibreboards (MDF) (Chew *et al.,* 1991). Research has also indicated that kraft pulp from oil palm stems can be used as a reinforcing material for cellulose fibre reinforced cement boards (CFRC) (Abraham, 1998). Other uses that have been investigated include the briquetting of the oil palm stem together with empty fruit bunches and pressed fruit fibres, into solid fuel pellets. Apparently, the calorific value of the fuel pellets produced is very similar to that of most tropical hardwoods, i.e. about 17.8 MJ/kg. Under controlled conditions, it is also possible to convert oil palm stems into fermentable sugar to produce alcohol fuel through enzymatic activity (Hoi *et al.,* 1991).

Research carried out at the Forest Research Institute of Malaysia (FRIM) has indicated that oil palm trunks may also be exploited commercially for various purposes, such as for manufacturing composite panel products, like medium density fibreboard (MDF), block board, laminated veneer lumber (LVL), mineral-bonded particleboard and plywood. Other proposed uses include furniture and paper making. The latest research by Bakar *et al*. (2006) and Chong *et al.* (2010) revealed that if properly treated, oil palm wood could be used for high grade furniture and as construction materials. Figure 8 shows an example of phenolic resin-treated oil palm wood in comparison to untreated oil palm wood.

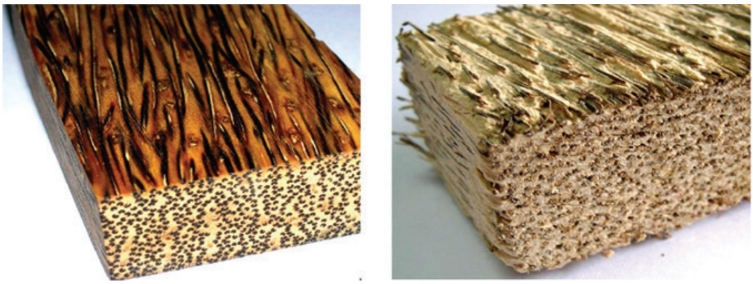


Figure 8 Resin-treated (left) and untreated oil palm wood (right)
Source: Bakar *et al*. (2006)

WOOD QUALITY ENHANCEMENT

The increasing global demand for timber products has resulted in a depleting supply of high quality traditionally known timbers from tropical forests. Currently, interest has shifted towards the use of lower density timbers that have good appearance and acceptable machining properties, comparable to those of commercial hardwoods. Most low density wood, classified as LHW, is inferior in strength, dimensional stability and durability against biodeteriorating agents. Nonetheless, once properly treated, these timbers can be converted into high value-added products. Several chemical modification techniques, such as bulking, internal coating and crosslinking, have shown satisfactory results in enhancing the quality of low density timbers (Hill, 2006).

Theory of Wood Modifications

Modification of wood involves two phases: active modification and passive modification. Chemical modification, thermal modification and enzymatic modification belong to active modification, which results in a change in the chemical nature of the material. Meanwhile, passive modification does not result in a change in the chemical nature of the material, but involves changes in its properties. Norimoto and Gril (1993) classified modification by referring to the changes taking place at the cell wall level, as illustrated in Figure 9. The subdivisions of the different wood modification methods are summarised in Table 10, with reference (where relevant) to Figure 9. For example, wood modified with chemical reagents, such as anhydrides and crosslinking agents, involved the formation of a single chemical bond with the hydroxyl groups of cell wall polymers (Figure 9d), or crosslinking between two or more hydroxyl groups

(Figure 9e) resulting in new properties for the modified wood, due to the changes in the chemical nature of the cell wall polymers. Examples of passive modification include impregnation of wood with phenol formaldehyde and methyl-methacrylate (MMA). The treated wood yields a, b and c (Norimoto & Gril, 1993). The chemicals penetrate and bulk into the cell wall and/or cell lumen, which may be responsible for the new properties (Hill, 2006). The chemical nature of the cell wall polymer in impregnation modified wood is changed if there is any chemical bonding formed between the impregnated molecules and the cell wall polymer.

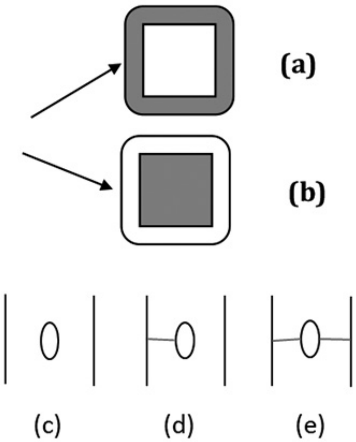


Figure 9 Diagram illustrating different types of wood modification at the cellular level (adapted from Norimoto & Gril, 1993)

Table 10 Classification of wood modification methods (see Figure 9)

Division	Type	Class	Illustration
Active	Chemical modification	Cell Wall Surface	d, e
Passive	Impregnation modification	Cell wall fill Lumen fill	a, c b

Wood Modification and Dimensional Stability

Wood is hygroscopic in nature. When wood is exposed to cyclical humidity changes, water molecules escape from the wood cell wall if the humidity in its surroundings is low and alternately, penetrate into the wood cell wall if the humidity is high. As a consequence, wood will shrink where the water molecules escape from the wood cell wall and swell as the water molecules penetrate the wood cell wall and become bound to the cell wall components through hydrogen bonding (Rowell & Banks, 1985). Swelling increases until the cell wall is saturated with water. This is known as the fibre saturation point (FSP). Water added beyond this point remains as free water in the lumen and does not cause further swelling. This process is reversible and accounts for the dimensional changes that occur when wood comes into contact with water vapour or liquid. There are two basic types of wood treatments for dimensional stability: 1) those which reduce the rate of water vapour or liquid absorption but do not reduce the extent of swelling to any great degree; and 2) those which reduce the extent of swelling and may or may not reduce the rate of water absorption.

The dimensional instability of wood is one of the disadvantages that limits its use. Efforts in enhancing the dimensional stability of wood have therefore been pursued by many wood scientists since a few decades ago. Stamm (1964) classified the methods used to reduce swelling in wood and/or reduce the rate of water vapour or liquid uptake into 5 classes:

1. Mechanical restraints by cross-laminating
2. Application of internal or external coatings
3. Reduction in the hygroscopicity of wood
4. Chemically crosslinking cell wall components of the wood
5. Bulking the wood cell walls with chemicals

A variety of terms are used to describe the degree of dimensional stability given to wood by various treatments: anti-swelling efficiency (ASE), moisture excluding efficiency (MEE) and Water repellency (WR) (Rowell & Youngs 1981).

ASE is calculated as:

$$S = 100\ [(V_2 - V_1) / V_1)]$$

where, S = volumetric swelling coefficient %; V_2 = wood volume after humidity conditioning or wetting with water in mm^3 ; and V_1 = wood volume of oven dried sample before conditioning or wetting with water in mm^3. Then,

$$ASE = 100\ [S_2 - S_1) / S_1)]$$

where, ASE = anti swelling efficiency resulting from a treatment (%); S2 = treated volumetric swelling coefficient (%); and S1 = untreated volumetric swelling coefficient (%).

The effectiveness of coating treatments in reducing water or liquid uptake is measured in terms of MEE (%) or WR (%), which is calculated as:

$$MEE = 100\ [W_2 - W_1] / W_2)$$

where, W_1 = weight gain in coated sample due to moisture pickup at 25°C, 97% relative humidity (RH) for 7 days (g); and W_2 = weight gain in uncoated control sample under the same conditions (g).

$$WR = 100\,[(T_1 - T_2)\,/T_1)]$$

where, T_1 = tangential swelling of control in 30 minutes of water soaking (mm); and T_2 = tangential swelling of treated samples under the same conditions (mm).

Mechanical Restraints by Cross Laminating

Wood is anisotropic, which means it has different shrinkage and swelling properties in three plain directions - radial, tangential and longitudinal. Wood swells in water 30 to 100 times more in the radial and tangential directions than in the longitudinal direction. As a result, plywood consists of veneers which are glued perpendicular to one another and each ply is mechanically restrained from swelling (Figure 10). Plywood will swell in the thickness direction, but it is very stable in the two cross-ply longitudinal directions as long as the glue joint holds.

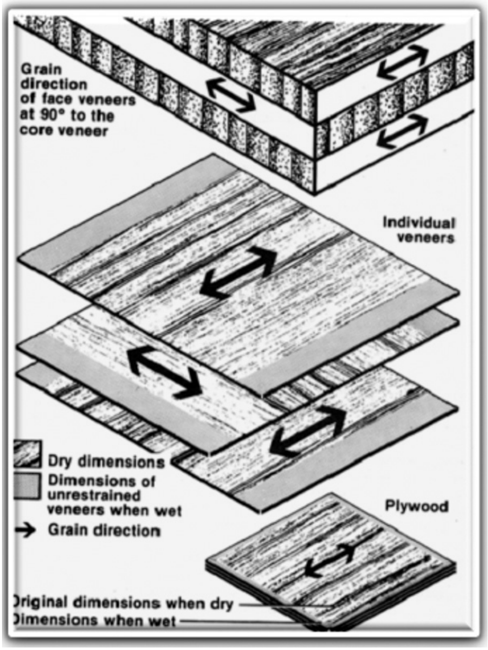


Figure 10 Plywood consists of veneers which are glued perpendicular to one another and each ply is mechanically restrained from swelling

Source: Haygreen and Bowyer (1982)

Water-Resistant Coatings

Any chemicals or substances that are resistant to water are suitable to be used as coating to apply on wood to reduce the rate of moisture uptake when exposed to moist conditions. Water resistant coatings can be applied either to the external surface of wood or to the internal surface (lumen walls). Water resistant coatings do not impart permanent dimensional stability to the treated wood as this treatment is only effective in reducing the rate of moisture uptake (Figure 11). The effectiveness of this treatment is thus usually evaluated in terms of Moisture Excluding Efficiency (MEE). Wood, applied with different external coatings, such as aluminium foil, paints, varnish or enamel and surface wax, yields different values of MEE. Meanwhile, wood wrapped in aluminium foil sheets and coated with layers of varnish results in MEE values of up to 99%, 60 to 90% for two coats of pigmented oil-based paints over an oil primer and 50 to 85% for two coats of varnish or enamel. Penetrating oils and surface wax treatments give MEE values of below 10% (Rowell & Youngs, 1981).

Chemicals, such as natural resins, waxes or drying oils dissolved in a volatile solvent, form hydrophobic polymers in the lumens or cell walls of treated wood. Wood can be treated with vinyl monomers such as methyl methacrylate (MMA) which is one of the internal coating treatments (Meyer, 1977). MMA monomer polymerised *in situ* under heat with catalysts or with gamma radiation forms a polymer called polymethyl methacrylate (PMMA). Most of the PMMA are located in the cell lumens, while little or no PMMA is formed in the cell wall (Figure 12). The rate of water uptake is thus greatly reduced as the void spaces in the wood structure are filled with PMMA. MMA treatment can reduce the water absorption of mahang (*Macaranga* sp.) by up to 94% (Ang *et al.,* 2009). However, if the treated wood is exposed to water vapour or liquid water long enough, the wood will swell to the same extent as untreated wood. It has also been reported that ASE of MMA-treated mahang wood increased with the addition of crosslinking agents. This product is more dimensionally stable (ASE, 36-42%) in high humidity (water vapour) conditions as compared to products treated without crosslinking agents (ASE, 21.9%). When in contact with liquid water, however, the ASE values for both products are the same (48 to 51%).

Figure 11 Water resistant coating to reduce moisture uptake

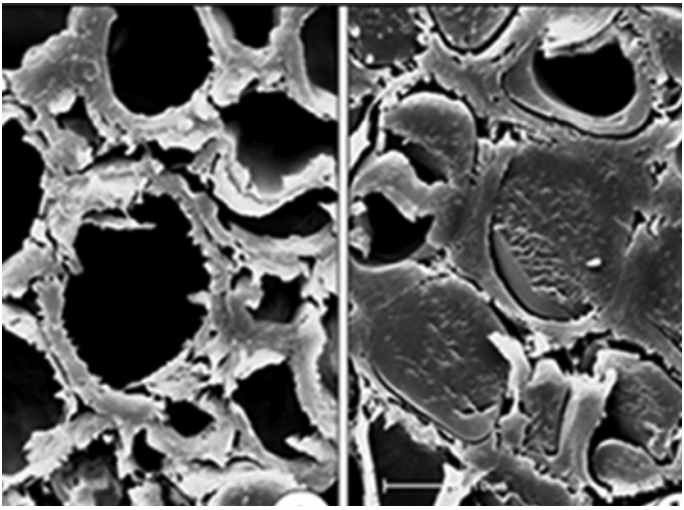


Figure 12 a) Untreated wood; and b) PMMA-treated wood which shows that PMMA filled the cell lumens of the wood forming an internal coating

Hygroscopic Reduction

The wood cell wall is built up with cellulose, hemicellulose and lignin, which comprise many hydroxyl groups (Figure 13). If wood is exposed to humid conditions, water molecules will penetrate into the cell wall and bond with the hydroxyl groups in the cell wall polymers. The cell wall then expands to accommodate the water molecules. If the hydroxyl groups on the cell wall polymers are removed however, there will be no more bonding sites for the water molecules. Any treatment that reduces the tendency of wood to take on water will result in a reduction in the tendency to swell (Rowell & Youngs, 1981). The optimum treatment would thus be to remove the hydroxyl groups in the cell wall polymers thus removing the sites for hydrogen bonding to water. One of the possible methods to reduce the hygroscopicity of wood is heat treatment. Heating wood in the absence of oxygen to temperatures up to 350°C for a short period of time results in a 40 percent reduction in swelling (R or ASE = 40 percent) (Serbog *et al.,* 1953). Doing so at lower temperatures for longer periods of time produces the same results. The reduction in hygroscopicity is attributed to thermal degradation of the hemicellulose component of the cell wall (Stamm, 1956). Hemicellulose, the most susceptible to thermal degradation, is the most hygroscopic of the cell wall polymers. Its degradation products polymerise under heat to produce a water-insoluble polymer. Heat treatment, for example, 280°C for 10 min, will result in 40% ASE and also in a 90 percent reduction in abrasion resistance, 40 percent loss in toughness, 20 percent loss in hardness and a 17 percent loss in modulus of rupture.

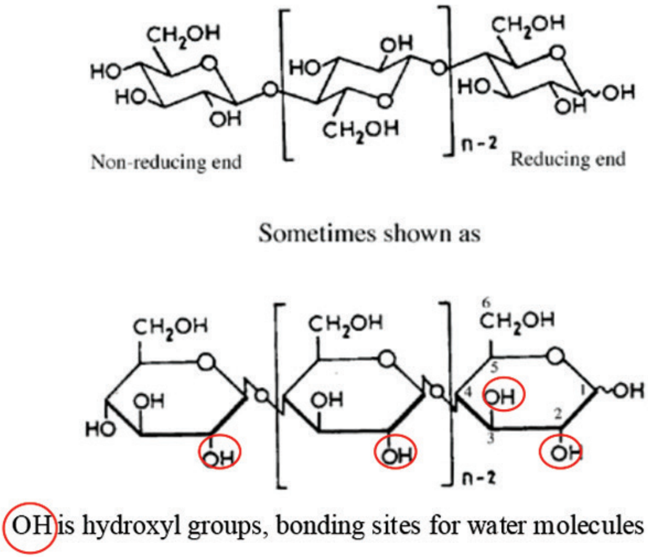


Figure 13 Structure of cellulose in the cell wall of wood. If OHs are removed, there will be no more bonding sites for the water molecules, and thus the swelling of the cell wall will be reduced

Heat treatment method was not commercialised earlier because the processes were complicated in large scale production due to the high temperature needed to get good biological durability. The problem has been with the wood burning if shielding gas is not used. There have also been problems in getting the heat effect to be even inside the wood, without surface charring. Moreover, the treatment also decreased wood's strength making it too brittle for many applications. In the late 1990s, however, Finland developed an advanced method of heat treatment of wood. The product, called ThermoWood (Jamsa & Viitaniemi, 2001), is produced by heating wood in a kiln at high temperatures of 180 - 250°C and using water vapour or nitrogen as the shielding gas. The process is divided into three phases (Figure 14).

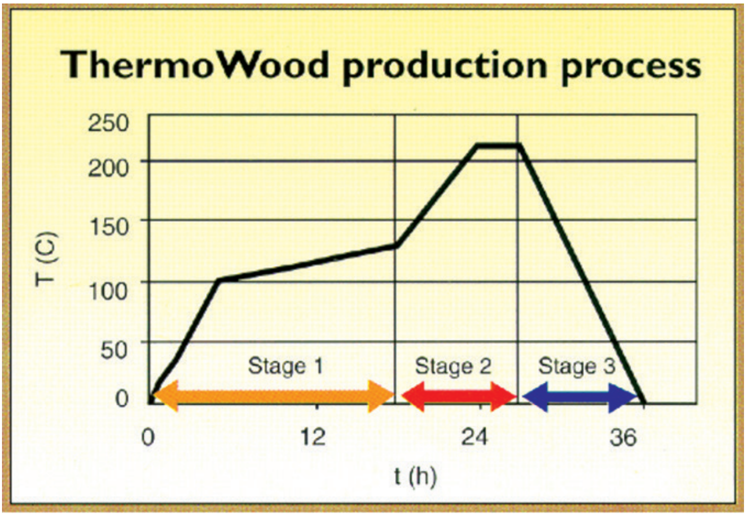


Figure 14 ThermoWood production process

Source: Jamsa & Viitaniemi (2001)

The first phase is the rise in temperature. Using heat and steam, the kiln temperature is raised rapidly to a level of around 100ºC. Thereafter, the temperature is increased steadily to 130ºC, during which time high-temperature drying takes place and the moisture content in the wood decreases to nearly 0. Phase 2 is the heating treatment. Once high-temperature drying has taken place, the temperature inside the kiln is increased to between 185ºC and 215ºC. When the target level has been reached, the temperature remains constant for 2–3 hours depending on the end-use application. Phase 3 is cooling and moisture conditioning. The final stage is to lower the temperature by using water spray systems. When the temperature has reached 80–90ºC, re-moisturising takes place to bring the wood moisture content to a useable level, 4–7%.

In Finland, ThermoWood is produced from pine (*Pinus sylvestris*), spruce (*Picea abies*), birch (*Betula verrucosa*/*pubescens*) and European aspen (*Populus tremula*), although other species are also treated. The ThermoWood process normally changes the colour of the wood to brown or dark brown, reduces equilibrium moisture content (EMC) by 50%, reduces shrinkage and swelling by 50-90%, improves biological durability and reduces thermal conductivity. The process also reduces the mechanical properties of the wood by 0-30% (Jamsa & Viitaniemi 2001).

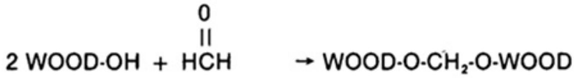
Another method of heat treatment of wood is using vegetable oils. Oil heating treatment of wood at high temperature has been used by several researchers (Sailer *et al.,* 2000; Wang & Cooper, 2005; Welzbacher & Rapp, 2005; Manalo & Acda, 2009; Umar *et al.,* 2016). Vegetable oils such as palm, linseed, rapeseed, coconut, soybean and sunflower oils are non-toxic and inexpensive. These oils are good heat transfer media and have high boiling points suitable for heat treatment of wood. Oil-heated wood is claimed to have better performance than air-heated wood. Under the same treatment parameters, wood treated with oils had better properties and decay resistance than wood dried using an oven in the presence of oxygen (Hill, 2006). The oxidative process during heat treatment reduces the strength of wood faster under aerobic conditions compared with that under anaerobic conditions. Oils are a good heating medium as they are able to transfer heat to the wood more readily and equally. They are also able to prevent oxygen from reaching the wood during treatment and lead to only a slight reduction in strength. It has been reported that *Pinus radiata* treated with linseed oil at 230°C for 3 hours can yield ASE value of 53% (Dubey *et al*., 2011). Oil absorption during treatment forms a protective layer on the wood surface, leading to enhancement in the dimensional stability of the treated wood (Tomak *et al.,* 2011). Wang and Cooper (2005) revealed that the oil-heat treatment of wood at 220°C for 4 hours can reduce EMC of the treated wood by 50%.

Umar *et al.* (2016) studied the optimisation of heating parameters in oil palm, i.e., temperature range of 150 - 220°C and time range of 2 – 4 hours, to enhance the resistance of rubberwood *(Hevea brasiliensis)* against white rot fungus. They found that a heating temperature of 228°C for 3 hours could maximise the resistance of the treated wood. The authors also revealed that treatment temperature is more crucial than treatment time in enhancement of decay resistance. Their results also showed that decay resistance is correlated to the degradation of cellulose and hemicellulose. Transformation of hemicelluloses from hydrophilic and easily digestible to hydrophobic molecules during heat treatment is also one of the possible factors that contributes to decay resistance.

Additionally, hydrothermal treatment with buffered pH medium (pH 8) has also been found to successfully lower EMC and increase the decay resistance of oil palm wood (Ebadi, 2015). Recent research has also shown that heat-treated wood is an environmentally friendly product as heat-treated wood does not release harmful compounds (Sabiha *et al.,* 2016). Leaching and toxicity tests showed that heat-treated kapur and Japanese larch at 180°C for 24 and 48 h did not release any harmful compounds that could harm the aquatic ecosystem.

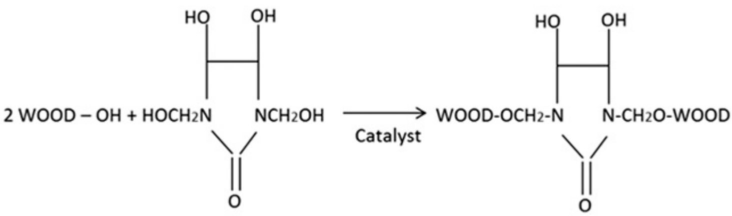
Chemically Crosslinking Cell Wall Components of the Wood

Hydroxyl groups of cell wall polymers can be chemically bound (crosslinked) through reaction with chemicals. If the structural units of the wood cell wall are crosslinked, the bonds restrain the units from swelling when moisture is present. One of the most common chemical systems for crosslinking is the reaction between wood cell wall hydroxyls and formaldehyde:



Crosslinking can take place between hydroxyl groups on the same or different cellulose, hemicellulose and lignin polymers. The reaction is usually catalysed with strong acids. A formaldehyde retention or weight percent gain (WPG) of 3.1% results in ASE of 47%, 5.5% WPG in ASE 60% and 7% WPG in ASE 90% (Stamm, 1959; Tarkow & Stamm, 1953). Since this system requires the addition of a strong acid catalyst to initiate crosslinking, all wood strength values are reduced. Moreover, the formaldehyde emissions from the treated wood is also high (Soljacic & Katovic, 1988).

The use of other crosslinking agents, which have longer chain length, could overcome this problem (Rowell & Youngs, 1981). Crosslinking agents that have longer inner carbon units, with more than one polyfunctional group per molecule such as dimethyloldihydroxyethylene urea (DMDHEU), have potential as stabilising agents. DMDHEU, a glyoxal-urea adduct, is a highly reactive dialdehyde, useful in crosslinking cellulosic materials. It has been used extensively as a crosslinking agent for textiles (Frick, 1971; Parikh & Reindhart, 1984). Reaction of DMDHEU with cellulose is outlined below:



Exploratory work by Nicholas and Williams (1987) found that wood treated with low concentration (5% solids) of an aqueous DMDHEU exhibiting an ASE as high as 53% can be achieved with a metal salt catalyst system and a curing of 160^{0}C. The authors studied the effects of temperature on ASE and noted that the value of ASE gradually decreased as the cure temperature decreased. By using proper selection of the catalyst system and cure temperature, strength loss can be reduced. In another study, Ashaari *et al.* (1990a, 1990b) used Lewis acid salts (methane sulphonic acid) as a catalyst system and curing temperature of 55°C and 80°C to treat sweetgum (*Liquidambar styraciflua* L.) and southern pine (*Pinus taeda* L.). ASE values ranging from of 46% to 64% could be achieved for both woods at WPG of 7-8%. A slight reduction of mechanical properties was found for wood cured at 55°C, but a significant reduction was found for wood cured at 80°C. Other non-formaldehyde crosslinking agents, which are able to stabilise wood, are glyoxal and glutraldehyde. With these agents catalysed by sulfur dioxide, values of ASE beyond 70% could be achieved in sitka spruce when the weight gains exceeded 20% (Yasuda & Minato, 1995).

Elimination of irreversible swelling of compressed wood can be done by treating with non-formaldehyde crosslinking reagents, i.e., glyoxal (Yasuda & Minato, 1995). With this treatment, the irreversible swelling of compressed wood is eliminated due to the formation of ester bonds as well as ether bonds between glyoxal and wood components. The addition of glycol into the glyoxal solution strengthens the linkages and will not leach out, even with repeated hot water soaking, hence, the weight and ASE of the treated wood can be retained.

Bulking Treatments

By adding chemicals within the cell wall, which will occupy space that water would otherwise occupy if the wood absorbs moisture, it is possible to keep the cell wall bulked and maintain its swollen state. It has been shown that the increase in wood volume upon treatment is directly proportional to the theoretical volume of the chemical added (Rowell & Ellis, 1978). The volume of wood increases with increasing chemical added to about 25 WPG, at which point the treated volume is approximately equal to the green volume (Rowell *et al.,* 1976). When this bulked cell wall comes into contact with moisture, none or very little additional swelling can take place. This is the mechanism for the effectiveness of bulking treatment on dimensional stability. Bulking treatment can be divided into three classes: non-bonded and water leachable; non-bonded and water non-leachable; and bonded and water non-leachable (Rowell & Youngs, 1981).

Nonbonded-leachable

The wood cell wall can be bulked with concentrated solutions of salts or sugar, such as sodium barium, magnesium and lithium chloride and solutions of sucrose, glucose and fructose. These chemicals are also very soluble in water and easily leached if the treated wood comes into contact with water (Figure 15). The treated wood is thus more hygroscopic and heavy finishing is needed to seal the chemical into the wood to prevent it from leaching when it comes into contact with water.

Another potential treatment utilises polyethylene glycol with molecular weight of less than 1000 (PEG-1000). Wood is usually treated in green condition with 30% by weight solution of PEG-1000 and the PEG is exchanged for the cell wall water. Wood treated with PEG-1000 gives a maximum ASE of 80% at 45 WPG

(Stamm, 1959). The strength properties of PEG-treated wood approximate those of untreated green wood. Fukuyama and Urakami (1983) reported the ASE value for PEG- treated sitka spruce as approximately 96% at 52.4% polymer content. Research on bulking of wood cell walls with polyacrylate with molecular weight ranging from 20,000 to 200,000 has also been conducted (Vasisth, 1986; Ashaari *et al.,* 1990a). In this case, partially green wood was treated with small quantities of acrylic polymer and the results indicate that the treatment decreased the swelling and reduced checking, warping and twisting of both hardwoods and conifers.

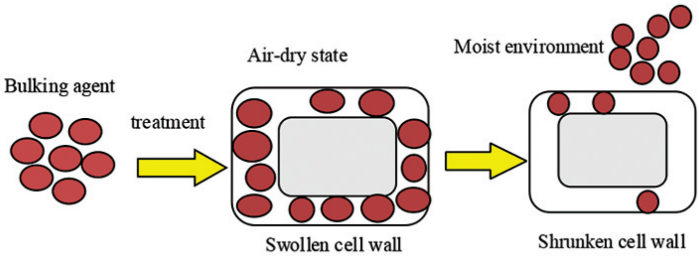


Figure 15 Illustration of non-bonded and leachable bulking treatment. The bulking agent filled and swelled the cell wall under air-dry conditions but will leach out when exposed to moist conditions, leading to shrinkage of the cell wall.

Non-bonded and Non-Leachable

Aqueous solution of phenol formaldehyde (PF) can bulk the wood cell wall and form insoluble polymers which will not leach out in water (Figure 16). Green thin wood or veneers are usually treated with this resin compound and after uniform diffusion of the resinoids into the cell wall structure, the wood is partially dried and the resin is then cured at about 150°C for 30 minutes. The resulting product is known as *impreg*. At weight gains of 25 to 40% resin, the treated wood will have an ASE of 60-70% (Stamm & Seborg, 1943). In addition, the treatment improves the electrical properties and acid resistance of the *impreg* product.

When phenol-resin-treated wood is highly compressed before curing of resin, a product commonly known as *compreg* is produced. Normally, *compreg* with a specific gravity of 1.3-1.4 containing 30% PF is achieved by applying a pressure level of 1,000 to 1200 psi at the temperature of 150°C (Stamm & Seborg, 1944). An ASE of 95% has been recorded for *compreg* products (Rowell & Youngs, 1981), with a very slow rate of water pickup where complete swelling equilibrium of a 1/2-inch sample is not completed even after a year at room temperature.

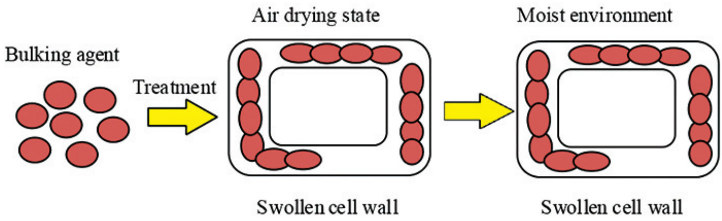


Figure 16 Illustration of non-bonded and non-leachable bulking treatment. The bulking agent fills and polymerises the cell wall upon heating and will not leach out when exposed to moist conditions.

Bonded and Non-Leachable

In this mechanism, organic chemicals are added to the hydroxyl groups of the wood cell wall components to form stable bonds. This type of treatment reduces hygroscopicity of the wood and at the same time bulks the cell wall with a permanently bonded chemical (Figure 17). An ideal chemical for this treatment should be capable of reacting wood with hydroxyls under neutral or mildly alkaline conditions at temperatures below 120°C, and the chemical system must be capable of swelling the wood structure to facilitate penetration (Rowell, 1975). Chemicals such as anhydrides, epoxides and isocyanates have been used to chemically modify wood. These chemicals give ASE value of 70-75% at WPG of 20-30%. However, in the case of epoxy and isocyanates, reactions are above 35% WPG and the ASE starts to decrease due to the volume of the added chemical which becomes great enough to rupture the cell wall (Rowell & Ellis, 1978). Water then interacts with the newly exposed ruptured cell wall component hydroxyl groups and causes the wood to super swell above the green volume.

Acetylation using acetic anhydride is the most studied reaction and the only one that has been commercialised. With acetylation, other than reducing the dimensional instability of wood, this process can also increase resistance against biodeterioration agents (Rowell, 2012). In the acetylation process, reaction takes place within the wood cell wall, where cell wall polymeric hydroxyl groups react with the anhydride, forming ester bonds and producing acetic acid as a by-product (Hill, 2006). Acetic anhydride reacts most readily with cell wall lignin and hemicellulose, to some degree, although cellulose remains essentially unmodified (Jebrane *et al.,* 2011). Acetylation is commonly performed with organic solvents or in the presence of a catalyst, such as pyridine and trimethylformamide (Li *et al.,* 2009).

Rowell and Youngs (1981) revealed that at least three factors must be considered in selecting a treatment to achieve product stability to moisture. The most important factor is the environment of the end product. For example, if the product comes into contact with water, non-leachable or bonded-treatment is needed. If, however, the product will be kept in an indoor environment, a leachable or water-repellent treatment might be satisfactory. The second factor is the degree of dimensional stability. If very rigid tolerances are required in a product such as in pattern wood dies, a treatment with very high ASE value is needed. If, on the other hand, a moderate degree of dimensional stability will be satisfactory, a less rigorous treatment will suffice. A final consideration is the cost effectiveness of a treatment. For example, the millwork industry uses a cheap simple wax dip treatment to achieve a moderate degree of water repellency. A higher degree of water repellency or dimensional stability may incur higher treatment costs that may not be offset in the marketplace. On the other hand, musical instrument makers require a very high degree of dimensional stability and the value of the final instrument can absorb the high cost incurred to accomplish the desired results. Figure 18 exhibits the various wood treatments and the degree of dimensional stability achieved.

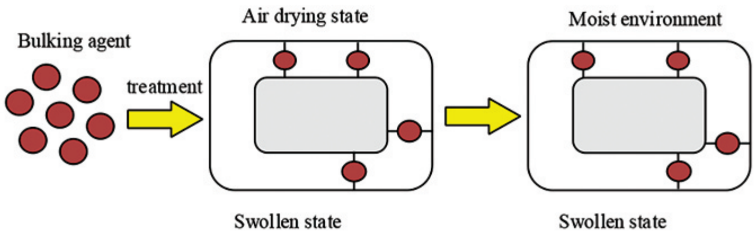


Figure 17 Illustration of bonded and non-leachable bulking treatment. The bulking agent fills and bonds with the hydroxyl groups of the cell wall and will not leach out when exposed to moist conditions

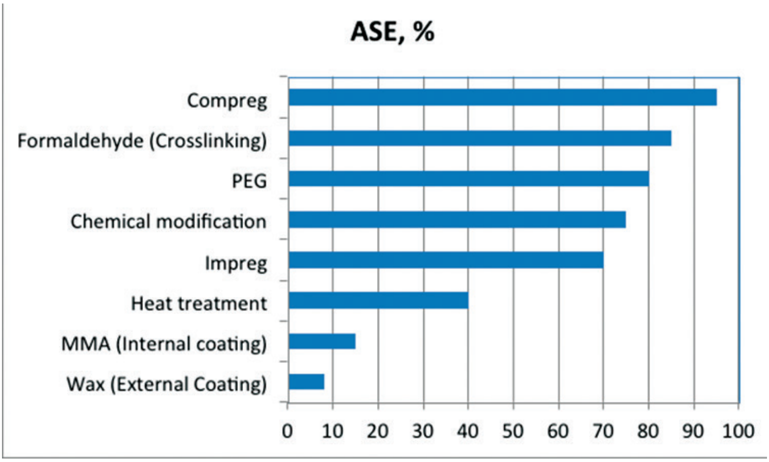


Figure 18 A comparison of various wood treatments and the degree of dimensional stability achieved (Rowell & Youngs, 1981)

CURRENT RESEARCH ON WOOD PROPERTY ENHANCEMENT

A series of works has been conducted at the Faculty of Forestry, Universiti Putra Malaysia, with the aim of enhancing the properties of low density tropical hardwood, oil palm wood and bamboo, through bulking treatment with phenol formaldehyde (PF) resin. Bulking treatment using PF resin can be categorised into 2 processes, namely, impregnation and compregnation processes. Impregnation refers to the process where the wood samples are impregnated with PF resin, followed by curing under heat, while compregnation involves compression of the wood at high temperature after the impregnation process. Products that are produced using the aforementioned processes are called impreg and compreg, respectively. Another product called the laminated compreg wood is produced following the precedent theories. This product is fabricated from the PF-impregnated wood strips, followed by compressing it in laminae form under high temperature using hot press (Figure 19). The aim of the treatments is to enhance the dimensional stability, mechanical strength and durability against biodeteriorating agents. Low density tropical hardwood, such as sesenduk (*Endospermum diadenum*), jelutong (*Dyera constulata*) and mahang (*Macaranga spp*.), are some of the species which have not been fully utilised due to their poor strength properties. Nonetheless, once they are properly treated, these timbers can be converted into high value-added products.

Works on enhancement of the low density wood properties have been initiated by Zaidon *et al.* (2009), who treated wood strips (5-mm thick) of sesenduk, jelutong and mahang with low molecular weight phenol formaldehyde (LMWPF, MW=600), followed by laminating and compressing them in a hot press to form three-layered compreg laminates. They found that the density of the 12-mm thick compreg laminates increased by two to three times that of the control samples. Shear stress at the bonding line was slightly lower or comparable, while the hardness was higher, than that of untreated wood. The ASE values of the compreg were in the range of 60-70%, and the mechanical properties increased to some extent as a result of the treatment. This study has been succeeded by a series of works focusing on various variables in order to improve the properties of low density wood.

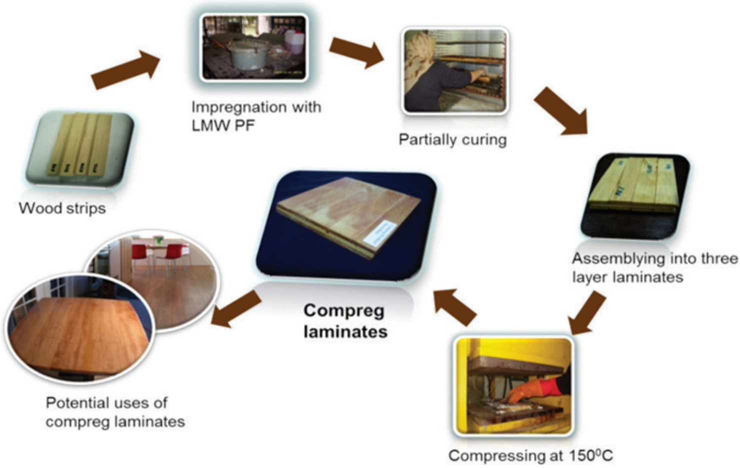


Figure 19 Fabrication of the laminated compreg products

Treatability of Wood with LMWPF

Treatability of the wood is expressed in weight percent gain (WPG) or polymer loading after treatment. Density and mechanical properties of compressed wood increase with increasing polymer loading, coupled with the densification process (Yano *et al.,* 2001). High polymer loading in compressed wood can be achieved by optimising the processing variables. These include molecular weight (MW) of the PF resin, concentration of the PF resin, impregnation process, pre-curing time and compression ratio (Zaidon *et al.,* 2104; Zaidon *et al.,* 2012).

Molecular Weight of PF resin

PF resin MW of 290-480 is able to penetrate into the cell wall and significantly reduces swelling (Rowell, 2005). Upon heating, this low molecular weight PF resin has a softening effect, which plasticises the cell wall, and once compressed (under hot pressing), the pressure deforms the cell walls easily without being ruptured. Once the resin is cured, the compressed wood remains intact, stronger and dimensionally stable (Yano *et al.,* 1997). If higher molecular weight PF resin is used (i.e., 820) however, the resin tends to be immobilised upon compressing and the bigger portion will remain in the cell lumen. As a result, there will be an apparent lack of compaction even though the weight gain is more or less the same. Most of the cured resin would stay in the cell lumen which will not provide significant stability to the wood (Furuno *et al.,* 2004). With the same solid content, resin with higher MW has higher value of mass per amount of substance and generally higher viscosity and lower wettability (Johnson & Kamke, 1994). These attributes will lead to poor penetration into the wood surface compared to resin with lower MW (Nor Hafizah *et al.,* 2014). PF resin with MW of 600 has also been used as a treating solution for low density tropical hardwoods and bamboo where the results showed that the resin penetrates and bulks the cell wall resulting in increment in dimensional stability and strength properties (Zaidon *et al.,* 2010; NurIzreen *et al.,* 2011; Rabiatol Adawiah *et al.,* 2012; Purba *et al.,* 2014; Ang *et al.,* 2014; Aizat *et al.,* 2014; Anwar *et al.,* 2006, 2012).

Concentration of PF Resin

The effects of PF concentration on the performance of polymer loading of low density wood have also been investigated (Rabiatol Adawiah *et al.,* 2012; NurIzreen *et al.,* 2011). The WPG of treated sesenduk and jelutong increased as the concentration of the treating solution increased from 20 to 40%. However, the ASE value for the wood samples treated with 20% resin was found to be higher than those treated with 30% and 40% resin, even though the weight gain was lower. At higher concentrations, the solution had higher solid content and this may limit the penetration of the solute into the wood cell wall, thus reducing the degree of bulking. On the other hand however, the modulus of rupture (MOR), modulus of elasticity (MOE), hardness and shear stress increased as the PF concentration increased. The increase in the mechanical properties was found to be positively correlated to WPG. The authors also revealed that the performance of PF-treated jelutong is far superior to the untreated wood, whereby the properties were higher by 30% to 40%.

Impregnation Process

Wood to be treated may vary in treatability. A suitable treatment process that is capable of obtaining high polymer loading and deep solution penetration should thus be selected. Vacuum-pressure process is preferred for treating thicker air dried samples, while the diffusion process is suitable for wood with very high moisture content, although this process is time consuming. Most of our research is confined to the vacuum-pressure treatment. In this case, a pressure retort is used. The treating cycle consists of a 30-minute initial vacuum. The retort is filled with the treating solutions under vacuum. When the cylinder is completely filled with the solution, a pressure of 690 kPa is applied and maintained for 30 minutes at ambient temperature. Initial moisture content (MC) of the wood has a significant effect on PF-loading when using this process. Purba *et al.* (2014) found that at 15% MC, maximum retention is achieved with 30 minutes soaking while longer soaking time was required (i.e., approximately 120 minutes) for the samples with more than 30% MC, but the polymer retention was markedly higher than the former (Figure 20). At lower MC, more void volume is available in the wood sample which is able to quickly absorb and retain higher resin solution at the early stage of soaking. Higher

MC will facilitate diffusion of resin into the wood but it will be a very slow process. Hill (2006) states that to ensure occurrence of full cell wall penetration, sufficient time should be allowed for impregnated molecules to diffuse into intracellular spaces. The diffusion process has also been successfully applied to treat green oil palm wood (OPW) with LMWPF (Aizat *et al*., 2014). The results showed that a high polymer loading and complete penetration of resin are achieved when 5-mm thick samples were soaked in 30% LMWPF, followed by wrapping in plastic for 6 days. WPG of 70% was achieved through this process.

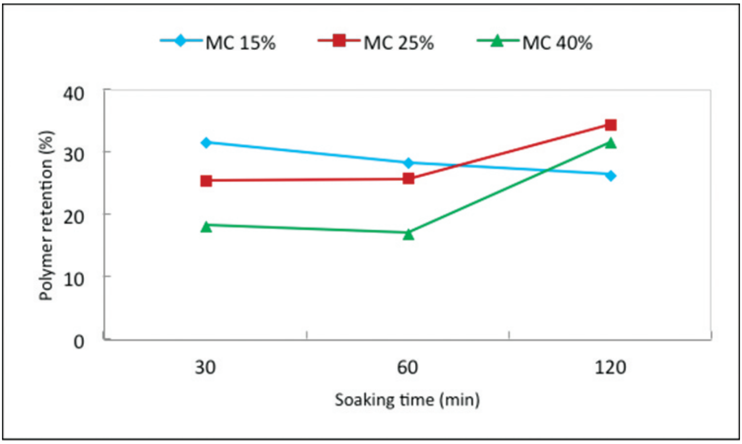


Figure 20 Polymer retention of impreg sesenduk at different initial moisture contents (Purba *et a.l*, 2014)

Compression Ratio (CR)

A crucial processing parameter to be considered in producing compreg is the compression ratio which is the compression pressure applied during the hot pressing of the products. CR is a ratio of the final thickness of product to the initial thickness before compression. The lower the CR the higher the compression pressure, calculated in terms of percentage. Higher compression pressure (low CR) used in the compregnation process will result in higher polymer loading. Zaidon *et al.* (2012) found that wood treated at 30% LMWPF would yield 58% and 71% polymer loadings when compressed at 80% and 70% CR, respectively. At lower CR, more resin fixes cell deformation and results in higher density of the product. Densification directly affects the properties of the resulting products as higher density will lead to higher mechanical strength, better dimensional stability and decay resistance.

Curing Parameters

Partially curing and curing parameters, such as curing temperature and time to cure the PF resin in the treated material were also investigated by our research group. These parameters determine whether the PF resin is optimally retained and cured in the treated wood. Before the curing process, the resin impregnated wood is heated at a mild temperature to partially cure the resin. The aim is to eliminate squeezing out of resin from the wood during the compression process in the case of compreg or to prevent checking or cracking on treated wood due to the immediate effects of high temperature curing. Our studies showed that partial curing temperature of 65-70°C for 6 hours and curing temperature of 150°C for 20-30 minutes are suitable to cure the LMWPF resin in 12-mm thick impreg or laminated compreg products made from low density woods (Rabiatol Adawiah *et al.,* 2012; Nur Izreen *et al.,* 2011; Zaidon *et al*., 2014).

Dimensional Stability of the PF-treated Wood

The dimensional stability of PF resin-products depends on the degree of bulking of resin in the wood cell wall, and it is positively correlated with polymer loading or WPG (Zaidon *et al.,* 2014). Our findings showed that the bulking treatment of wood with LMWPF successfully enhanced the dimensional stability of impreg, compreg and laminated compreg products. A summary of the results on dimensional stability is shown in Table 10. The results reflect that LMWPF (MW 600) is capable of bulking the cell walls of wood. During hot pressing, the methyl groups in the phenolic rings are converted to methylene bridges resulting in the formation of a very highly cross-linked thermoset polymer (Collins, 1996). The cross-linked polymer becomes hard, infusible, insoluble and cannot be softened or melted (Hon, 2003), and therefore, limits water molecules penetrating the cell wall when exposed to high humidity conditions.

The ASE values recorded for our compreg products were much lower that the ASE values of compreg veneer-based products of 80-90% (Rowell & Youngs, 1981). The discrepancy is plausibly caused by the spring back of the compressed sample due to the residual force that is exerted upon exposure to high humidity (Purba *et al.,* 2014). Zaidon *et al*. (2014) studied on the effect of the compression ratio on ASE of compreg sesenduk and found that ASE is inversely correlated to compression (Figure 21). It has also been reported that spring back also occurs in thinner samples treated with higher concentration of PF resin (Zaidon *et al*., 2010; Rabiatol Adawiah *et al.,* 2012). For fabricating laminated compreg wood, it is suggested that a CR of 80% will have a significant effect on the dimensional stability of the product. By compressing at this CR, laminated compreg OPW attained ASE of 68% (Aizat *et al.,* 2014).

Table 10 Mean physical properties of phenolic resin-treated wood

Species	Product	Density Kgm^{-3}	WPG %	ASE %	WA %	TS %
Mahang	Impreg	441	50.65	67.4	-	-
	Compreg	543	27.2	15.8	-	-
	LCP	-	-	-	-	-
	Untreated	315	-	-	-	-
Sesenduk	Impreg	797	127	40.02	41.35	3.10
	Compreg	787	64.35	20.30	30.57	4.57
	LCP	840	51.0	77.32	18.28	0.33
	Untreated	404	-	-	179	5.21
Jelutong	Impreg	744	85.31	15.0	35.9	3.01
	Compreg	803	58.49	51.87	27.75	2.14
	LCP	733	-	32.2	43.95	2.15
	Untreated	396	-	-	63.2	4.18
OPW	Impreg	-	-	-	-	-
	Compreg	-	-	-	-	-
	LCP	758	61.4	67.70	30.51	6.44
	Untreated	624	-	-	74.66	22.41

Incorporation of 1.5% nanoclay (based on solid PF) in LMWPF solution has also been found to impart higher dimensional stability of impreg sesenduk compared to that of wood treated with PF alone (Nabil *et al.,* 2015b). As can be seen in Figure 22, regardless of the PF solution concentrations, the ASE values of admixture-treated sesenduk wood are relatively higher than that of PF-treated wood.

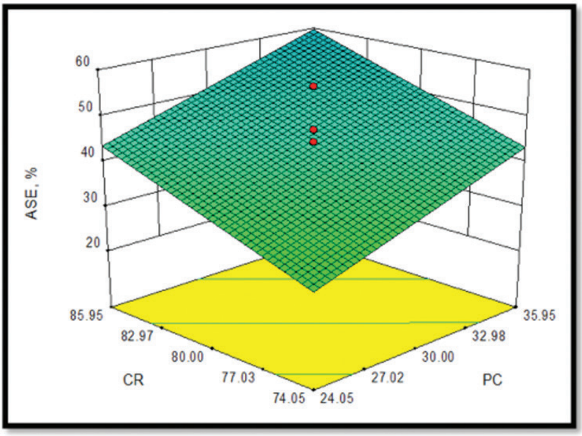


Figure 21 The 3D-surface plot of ASE as a function of polymer concentration (PC) and compression ratio (CR) at the fixed value of 6 h partial curing time (PCT)

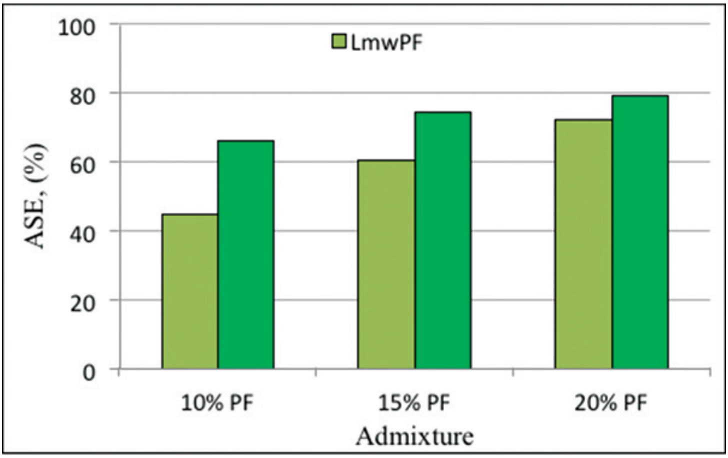


Figure 22 ASE values of sesenduk wood treated with LMWPF and admixture of LMWPF + nanoclay

Mechanical Properties of PF-treated Wood

The overall mechanical properties of the phenolic resin-treated wood, extracted from our studies at the Faculty of Forestry, UPM, are shown in Table 11. For the impreg mahang, the MOR and MOE in static bending were improved by 22- 59% and 38-78%, respectively. A higher percentage of changes in the compressive stress and hardness were also recorded for the compreg product (i.e., 165-307% and 68-266%, respectively) where the increment was negatively correlated with CR (Ang *et al.,* 2014). Lower CR used in the compregnation process resulted in increased density and at the same time the treated wood became rigid and hardened. Similar results were also recorded for the impreg and compreg products from jelutong and sesenduk wood (Nur Izreen *et al.,* 2011; Rabiatol Adawiah *et al.,* 2012). The increment in properties is very much related with WPG and density of the materials. Impregnation and compregnation processes are capable of improving the strength of jelutong from the strength group (SG) 7 (< 6600 N/mm^2) to SG 3 ($> 14,000$ N/mm^2) (Zaidon *et al.,* 2015).

The compregnation process also successfully increased the performance of laminated compreg OPW. When compared to the untreated OPW, the density of the product increased by two folds, MOR by 2-2.5 folds and MOE by approximately 10 folds (Aizat *et al.,* 2014). Meanwhile, the addition of nanoclay into PF resin further increased the mechanical strength of impreg sesenduk (Nabil *et al.,* 2015a & 2015b). This resin system can be used at a lower concentration to increase the performance of the treated wood at the same time (Figure 23). In the presence of nanoclay, the MOR, MOE, compressive stress and hardness of the impreg sesenduk are higher than that of wood treated using PF *per se.*

Table 11 The mean mechanical properties of phenolic resin-treated wood

Species	Product	WPG %	MOR Nmm^{-2}	MOE Nmm^{-2}	Shear Nmm^{-2}	Hardness KN
Mahang	Impreg	50.65	82.0	12276	-	-
	Compreg	27.2	69.7	9013	-	2.1
	LCP	-	-		5.73	3.65
	Untreated	-	57.3	6540	6.41	1.25
Sesenduk	Impreg	-	81.10	8135	-	2.14
	Compreg	64.35	95.45	9285	-	-
	LCP	51.0	73.17	5510	8.89	2.73
	Untreated	-	55.91	5064	8.80	1.41
Jelutong	Impreg	85.31	70.31	7752	-	-
	Compreg	58.49	92.65	11643	-	-
	LCP	-	73.17	5510	9.43	3.8
	Untreated	-	62.95	6124	7.53	2.5
OPW	Impreg	-	-	-	-	-
	Compreg	16.23	78.15	15046	-	-
	LCP	61.4	94.37	11134	1.47	-
	Untreated	-	54.57	1034	1.0	-

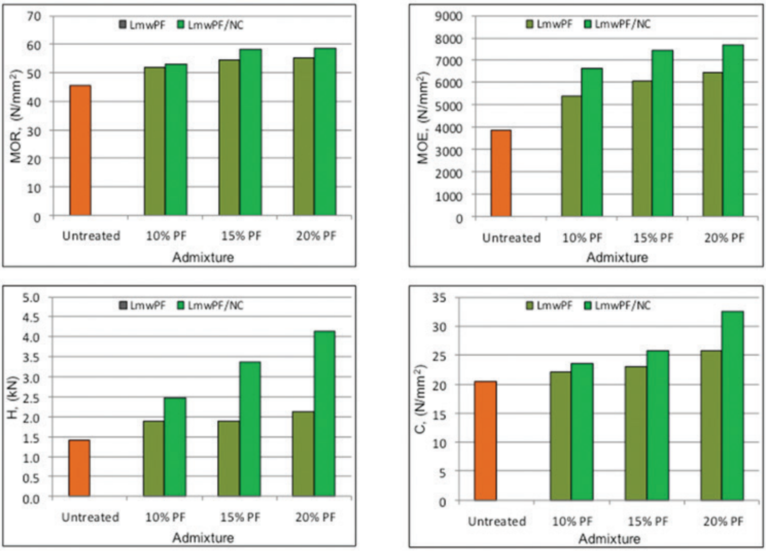


Figure 23 Mechanical properties of sesenduk wood treated with LMWPF and admixture of LMWPF + nanoclay (Nabil *et al.,* 2015b)

Durability against Termites and Fungal Decay

Sesenduk, jelutong and mahang timber are classified as non-durable under tropical climatic conditions. Oil palm wood, a non-wood lignocellulosic material, is also classified as non-durable or perishable due to its high sugar content. These materials are highly susceptible to biological degradation, such as by termites, fungi and insects. Among the conventional methods used to prolong the service life of wood materials is by treatment with preservatives, such as chromated copper arsenic (CCA), creosote or boron compounds. The preservation process, however, will only give long-term protection as it does not enhance the dimensional stability and strength properties of the wood materials. Meanwhile, the phenolic resin treatment is an alternative process to protect wood against fungal decay and termite attacks. Impreg mahang and jelutong, when subjected to rotting fungus (*Pycnoporus sanguineus)* in an accelerated laboratory test, experienced non-significant weight loss as opposed to 17.5% and 18.4% for the untreated mahang and jelutong wood, respectively (Ang *et al.,* 2014; Nur Izreen *et al.,* 2011). Similar results have also been reported for compreg jelutong and sesenduk, where the resistance against fungal decay increased by 96 - 99% (Lee & Zaidon, 2015; Rabi'atol Adawiah *et al.,* 2012). Great improvement in the resistance against termites (*Coptotermes curvignathus)* and rotting fungus *(P. sanguineus)* was also found for compreg oil palm wood. In particular, the resistance against termite attacks increased by 66 - 89% and by 47 - 93% against fungal decay. Bakar *et al.* (2013) revealed that the resistance increased as the compression level of the compreg OPW increased. The weight loss values for some phenolic resin-treated products when subjected to termite attacks and fungal decay are shown in Table 14. Figure 24 and Figure 25 exhibit the visual analyses of the impreg sesenduk after being exposed to fungal decay and termite attacks, respectively.

Table 14 The mean biological properties of phenolic resin-treated wood calculated based on weight loss

Species	Product	Against fungal decay (*P. sanguineus*)		Against termite attack (*C. curvignathus*)	
		Wt loss, %	Percent improvement, %	Wt loss, %	Percent improvement, %
Mahang	Impreg	2.14	85.73	-	-
	Compreg	0.0	100	-	-
	LCP	-	-	-	-
	Untreated	15	-	-	-
Sesenduk	Impreg	3.30	87.45	0.49	97.26
	Compreg	0.51	98.06	-	-
	LCP		-	-	-
	Untreated	26.30	-	17.95	-
Jelutong	Impreg	1.10	96.91	-	-
	Compreg	0.76	97.87	-	-
	LCP	-	-	-	-
	Untreated	35.64	-	-	-
OPW	Impreg	8.99	47.09	9.58	-
	Compreg	1.77	89.58	6.17	-
	LCP	-	-	-	-
	Untreated	16.99	-	27.94	-

The addition of nanoclay into LmwPF resin can further improve the resistance of the impreg sesenduk against termite attack and fungal decay (Figure 26). Although the improvement is not significant compared to treatment without nanoclay, the finding suggests that with the addition of nanoclay, lower PF concentration can be used to attain the desired level of resistance (Nabil *et al.,* 2016).

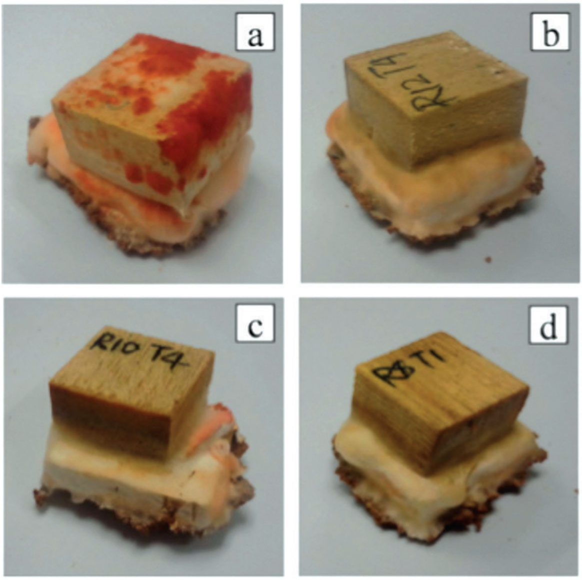


Figure 24 Sesenduk wood after 16 weeks of exposure to *Pycnoporus sanguineus*: (a) untreated sesenduk; (b) treated using 20% PF concentration; (c) treated using 15% PF concentration; and (d) treated using 10% PF concentration (Nabil *et al.,* 2016).

Figure 25 Sesenduk wood after 4 weeks of exposure to *Coptotermes curvignathus* Holmgren: (a) untreated sesenduk; (b) treated using 20% PF concentration; (c) treated using 15% PF concentration; and (d) treated using 10% PF concentration (Nabil *et al.,* 2016).

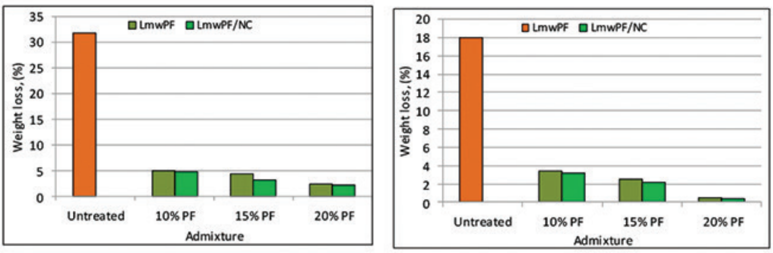


Figure 26 Mean weight loss of impreg sesenduk when exposed to Fungal deacy (left) and termite attack (right) (Nabil *et al.,* 2016).

Formaldehyde Emission of Phenolic Resin-treated Wood

There are a couple of drawbacks when using LMWPF resin in the bulking treatment of wood which are low curing rate of the resin (He & Riedl, 2003) and high formaldehyde emission by the treated product during soaking and hot pressing processes. Phenol formaldehyde resin is synthesised by reacting phenol (C_6H_5OH) and formaldehyde (CH_2O). Formaldehyde forms -CH_2- bridges between two phenol molecules producing hydroxymethyl groups followed by partial polymerization to the oligomer that makes up the resin (Figure 27, Frihart 2005). LMWPF resin is generally linear pre-polymer that contains substantial amounts of methylol groups in the oligomeric chains, where some of these methylol groups are released as free formaldehyde when exposed to high temperature and humidity (Hoong *et al.,* 2010).

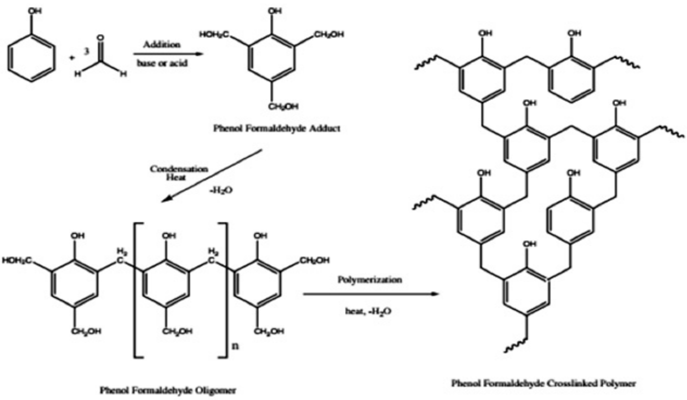


Figure 27 The reaction of phenol and formaldehyde to form hydroxymethyl groups, followed by partial polymerisation to the oligomer that makes up the resin. After impregnating into the substrate the polymerisation is completed to form a crosslinked polymer network.

This scenario is worse if higher concentration resin is used (Nur Izreen *et al.,* 2011). Formaldehyde emission (FE) increases when higher concentration of PF is used as the treating solution. FE of 64 mgL^{-1} is recorded for compreg sesenduk treated with 20% w/v PF, and the FE increases to 110 mgL^{-1} when treated with 40% PF (Rabiatol Adawiah *et al.,* 2012). The same result has also been reported for impreg jelutong when treated with higher concentration of PF (Nur Izreen *et al.,* 2011). One method to capture this free formaldehyde is to mix the treating solution with formaldehyde scavengers (Roffael, 1993). There are several potential scavengers which can be introduced into the treatment system to catch free formaldehyde. These include urea, ammonium hydroxide, ammonium carbonate, potassium sulphite and sodium thiosulphate. They are either mixed with the resin or applied on the wood surface, aimed at reducing the formaldehyde emission level of the treated wood. Urea is however, preferred due to its low cost, ability to reduce formaldehyde emission (Zaidon, 2009) and increase the degree of polymerisation, but it decreases the curing rate of the PF resin (Kim *et al.,* 1996). The introduced urea reacts with the free formaldehyde and forms a rigid cross-linked polymer of urea formaldehyde. Figure 22 exhibits the FE of impreg and compreg products treated with or without urea. Purba *et al.* (2014) and Rabi'atol Adawiah *et al.* (2012) revealed that the formaldehyde emission was greatly reduced when 30% urea (based on PF solid content) was added into the PF resin. However, this system adversely affects some mechanical properties of the treated wood. The FE reduction, however, is still high compared to the standard threshold limit of 0.16-2 mgL^{-1} (Markessini, 2010).

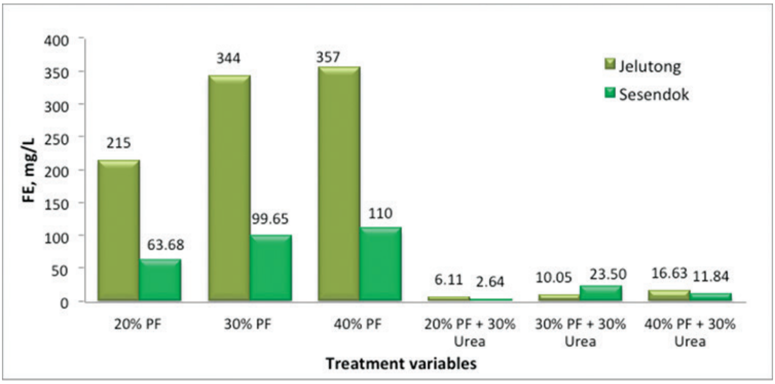


Figure 28 Formaldehyde emission of the impregnated jelutong and sesenduk wood treated with and without urea

Ammonium hydroxide has also been found to reduce FE from compreg sesenduk. An addition of 1% ammonium hydroxide (based on solid PF) in PF resin reduces FE from the treated wood, from 23.60 mgL^{-1} to 3.71 mgL^{-1} (Zaidon *et al.,* 2016). Meanwhile, applying ammonium carbonate (30 gm^{-2}) on the surface of impreg and compreg wood that had been treated with admixture of LMWPF + urea, was also found to further reduce FE (Zaidon *et al.,* 2015). A study by Mohamad Amarullah *et al*. (2010) found that modifying the compression schedule by employing stepwise pressing and extended heating in an oven for 24 hours could practically reduce FE of the compreg to a threshold safe limit. Using this process however, results in inevitable reduction in the strength of the product.

Glyoxalated organosolv lignin has been used to incorporate LMWPF resin with the aim of reducing the use of high amount of PF resin which may lead to high formaldehyde emission (Ang *et al.,* 2015a; 2015b; Ang *et al.,* 2016). The authors reported that impregnation with LMWPF and glyoxalated organosolv lignin (50:50 by weight) could reduce formaldehyde emission of impreg sesenduk by 50%. The ASE value obtained is comparable to that of wood impregnated with PF resin alone. Currently at the Faculty of Forestry, Melamine urea formaldehyde (MUF) of different proportions is being developed to treat wood and bamboo strips. A preliminary study showed that the resin is able to bulk in the cell wall of the lignocellulosic materials, with ASE of approximately 60% achieved with WPG of approximately 50%. At this point of time, the FE of the treated products is yet to be determined.

CONCLUSION

The timber industry, which has been a major source of export income for the country for the last 40 years, needs to innovate and re-invent itself in order to remain competitive. It is expected that the future growth of the industry will be through higher productivity, innovation and technological breakthroughs. Innovation, in this context, refers to the successful exploitation of new ideas and designs that result in tangible products and services. Meanwhile, technology involves the application of knowledge, equipment, machines and processes in translating innovations into newer and more sophisticated products for commercial gain. Hence, in order for the timber industry to remain relevant, it has to adopt new and state-of-the-art technologies to overcome production bottlenecks and produce newer and more sophisticated products.

The wood-based products industry in Malaysia is expected to face the problem of inadequate supply of raw materials to sustain the growth of the industry in the future. In other words, the supply of raw materials from natural and plantation forests may not suffice and the industries will have to seek alternative raw materials to augment the diminishing supply of traditional commercial timbers. Through innovation and R&D activities, the inferior properties of lignocellulosic materials, such as low density wood, OPW and bamboo, which are normally used for traditional purposes, can be enhanced and thus become alternative raw materials for the wood-based industries.

Various treatments to enhance the properties of these raw materials have been discussed in this lecture. One of the cost-effective treatments is through phenolic resin treatment. Phenol formaldehyde with molecular weight of 600 can bulk the cell wall structure of woody materials, and upon heating, will polymerise and render them insoluble in the wood and will not leach if the treated wood comes in contact with water. The resultant products, impreg or compreg, have dimensional stability, strength and hardness superior to that of untreated materials. One of the potential products, which has superior physical, mechanical and biological properties, and is expected to have commercial value, is laminated compreg wood. This product is fabricated by assembling PF resin-impregnated strips parallel or perpendicular to each other to form three layers of laminae, followed by compression in a hot press. Our findings from several intense research works at the Faculty of Forestry, Universiti Putra Malaysia, can be of use in diversifying the utilisation of inferior quality wood, agriculture waste and bamboo for higher value-added products such as heavy-duty parquet flooring, panelling, furniture components or moulding products.

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BIOGRAPHY

Zaidon Ashaari was born on 12 October 1960 in Dengkil, Selangor, Malaysia. He is married to Paridah Md. Tahir and has four children. Zaidon started his primary education at the Methodist National Type Primary School (MNTPS), Telok Datok, Banting, Selangor. He attended Sekolah Menegah Sains Selangor, Jalan Cheras, Kuala lumpur (now Bandar Tun Razak) for his secondary education followed by the Institut Teknolgi Mara, Shah Alam (now UiTM) where he obtained his Diploma in Wood Technology in 1982. Upon graduation from ITM, he was employed by Pusat Penyelidikan Atom Tun Ismail (PUSPATI, now Agensi Nuklear Malaysia) as an Experimental Officer. In May 1984, Zaidon was awarded the Japan-Asean scholarship to pursue his Bachelor and Master degrees at Mississippi State University, USA. He completed his Master of Science in Wood Science and Technology degree in March 1989 and joined the Faculty of Forestry as a tutor. He then went on to pursue his Ph.D at the Department of Forestry, University of Aberdeen, Scotland, in December 1991 and graduated three years later. He was then appointed as a lecturer at the Faculty of Forestry, UPM in September 1995.

Zaidon started late in his career as an academician. He was only promoted to Associate Professor in 2001 and to a full Professor in the discipline of Wood Quality Enhancement in 2012. Administratively, he was appointed as the Head of Department, Forest Production, Faculty of Forestry, from May 2001 until April 2006. In May 2009, he became Deputy Dean of Academic and International Affairs at the Faculty of Forestry and later in May 2013, he was again appointed as Deputy Dean, but with a different portfolio, Research and Innovation.

As a lecturer, Zaidon has taught various courses related to wood science but is known for his expertise in wood physics, wood drying, wood deterioration and control and non-wood forest products.

Zaidon has supervised more than 120 students at both undergraduate and graduate levels and most of these works have been published. To date, he has published more than 120 articles in numerous journals, where more than 50 have appeared in International and National proceedings, chapters in books, technical reports, as well as a number of consultation reports. He has also contributed 6 academic articles to the Encyclopaedia of Science and Technology.

Zaidon has vast experience in conducting research in the area of wood quality enhancement and utilisation of palm and bamboo. He has headed 13 research projects and collaborated with other researchers in more than 10 research projects. To date he has received more than RM1.5 million in research grants from MOSTI, MOHE and other public bodies. He has also received international funding from the International Timber Trade Organisation (ITTO) to work on the utilisation of small-diameter-logs from sustainable resources for bio-composites products. In addition, he has been involved in a number of consultancy projects for both the government and industry, such as that with the MTIB (RRIM 3000 clone study), TNBRD (Suppression of bamboo growth under high voltage transmission lines (HVTL) and wooden cross arms for HVTL, Golden Hope Sdn. Bhd. (bamboo overlayed parquet), IWK Sdn. Bhd. (wood quality of rubber trees fertilised with sewage sludge), RCP Technologies (effects of stimulants on rubberwood strength), APAFRI (development of databases of specialist networks), and MPOB (rattan quality in oil palm plantations).

Zaidon's involvement in extension work has been extensive. His expertise and commitment have been acknowledged by other organisations where he has been appointed as technical assessor/ expert to evaluate products for CIDB, research proposals for the E-science fund (MOSTI) and university grants and a business start-up fund (MTDC), as an external assessor for academic promotion to Professor (UNIMAS and UiTM) and as panel assessor for new bachelor degree programs (MQA). He sits on many research and academic committees, among others the Technical Working Group (TWG) for Wood Preservation Standard (MS544) (CIDB), TWG for Moisture Content of Timber (MTIB), Technical Committee for Rattan and Bamboo (MTIB), Advisory Committee in Product Certification system (MTIB), and Advisory Committee for the Department of Civil Engineering (Politeknik Sultan Salahuddin Abdul Aziz Shah, Shah Alam). Due to his active participation and devoted commitment to the awareness of forest sustainability, he has been appointed as head of judges for the National Natural Science Quiz organised by UPM-MOE-NRE for 4 consecutive years. He has also successfully organised and co-ordinated more than 10 training workshops related to wood drying and wood preservation for staff of government agencies and the wood-based industry and been a resource person in training workshops. Additionally, Zaidon has been entrusted to examine more than 30 Phd and Master theses in UPM and other public universities.

ACKNOWLEDGEMENT

Praise to Allah, the Most Gracious, the Most Merciful. Alhamdulillah, I am most grateful to Allah (SWT) for the faith and all the blessings in my life that have moulded me to the person I am today. Allah has given me this very meaningful opportunity to share my knowledge and experience in this inaugural lecture.

This humble effort could not have become a reality without the prayers and tremendous support from friends and family members, especially my beloved parents, Hj. Ashaari Jaman and Hjh. Puziah Ketik, and my four children, Zahirah, Zuheir, Zulfa and Zafirah.

I would like to thank Universiti Putra Malaysia for the opportunity to pursue my career as an academician. My sincere indebtedness to Dr. Kamis Awang (then the Dean of Forestry Faculty) and Dr. Razali Abd. Kadir (then the Head of Forest Production), who recruited me and convinced me that ***Wood Quality Enhancement*** was the area I should pursue. To my **MENTORS AND COLLEAGUES**, Prof. Dato' Dr. Nik Muhammad Nik Majid, Dr. Hamami Shari, Dr. Jalaludin Harun, En. Zin Jusoh, the late En. Ismail Hashim, Dr. Ahmad Said Sajap, Dr. Faizah Abood, Prof. Dr. Awang Noor Abd. Ghani, Assoc. Prof. Dr. Shukri Mohammed, Dr. Abdullah Mohd, Dr. Amat Ramsa Yaman Dato' Dr. Wan Razali, Dr. Khamurudin Md. Nor, Prof. Dr. Ahmad Ainuddin Nuruddin, Prof. Dr. Jegatheswaran Ratnasinggam, Prof. Dr. Nor Aini Abd. Shukur and Prof. Datin Dr. Faridah Hanum Ibrahim (Former Dean), I would like to express my gratitude for their wisdom and endless support.

I would also like to acknowledge the contributions of various organisations that have funded my research works, whether in cash or in-kind: Universiti Putra Malaysia, MOHE, MOSTI, MTIB, ITTO, Mississippi State University and the industry players particularly, Malaysian Adhesives and Chemicals Sdn. Bhd. Thank you for your generosity.

A big thank you also to **ALL MY STUDENTS (former and current),** who have worked by my side consistently. The work reported herein, as well as that published would have not been possible without your continuous hard work, commitment, enthusiasm and most of all, sincerity. To Dr. Singgaram Ayeru, Dr. Ang Aik Fei, Norhairul Nizam, Chot, Rafidah, Nordahlia, Izran, Nabil, Fikri, Anwar, Purba, Umar and Wan Nabila; and soon to be Dr.: Nabila, Aizat, Izreen, Adawiah, Fatin and Seyeed Eshaqh, as well as those names I could not list here, thank you very much and may god bless you always.

Sincere appreciation also goes to **MY COLLABORATORS:** Dr. Lee Seng Hua, Prof. Dato' Dr. Abd. Khalil Shawkatali, Prof. Dr. Kim Gyu Heok, Prof. Dr. Tadashi Nobuchi, Assoc. Prof. Dr. Edi Suhaimi Bakar, Assoc. Prof. Dr. Rasmina Halis, Assoc. Prof. Dr. H'ng Paik San, Assoc. Prof. Dr. NorAzowa Ibrahim, Dr. Khairun Anwar Uyup, Dr. Hamdan Husin, Dr. Mohamad Jawaid, Dr. Ali Karimi, Assoc Prof. Dr. NorYuziah Mohd Yunus, Dr. Sabiha Salim, Dr. Paiman Bawon, Dr. Mohd Nor Mohd Yusuf and Prof. Dr. Zakiah Ahmad.

I wish to express my sincere appreciation to the management and staff of Universiti Putra Malaysia, in particular those from the Faculty of Forestry and Institute of Tropical Forestry and Forest Products (INTROP), who have been supporting my career in many ways. My deepest gratitude to Sopian, Rahmat, Maiza Azura, Saudah, Fatimah, Alina, Siti Aisyah and Surinah for their efficient work and multi-tasking skills that have made my work easier.

Most importantly to my beloved wife, Prof. Dr. Hjh. Paridah Md. Tahir, you have been everything to me – a wife, partner, colleague, rival, advisor and inspiration throughout my journey to this feat. **TERIMA KASIH, TERIMA KASIH DAN TERIMA KASIH**

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