THE POTENTIAL OF OIL PALM TRUNK BIOMASS AS AN ALTERNATIVE SOURCE FOR COMPRESSED WOOD

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Compressed wood, which is formed by a process that increases the wood's density, aims to improve its strength and dimensional stability. Compressed wood can be used in building and construction, especially for construction of walls and flooring. Currently, supplies of wood are becoming limited, and the oil palm tree has become one of the largest plantation species in Malaysia. Oil palm trunk could be an appropriate choice for an alternative source for compressed wood. This paper aims to review the current status of oil palm biomass, including the availability of this tree, in order to illustrate the potential of oil palm biomass as an alternative source for compressed wood. Up to the present there has been insufficient information regarding the manufacturing conditions and properties of compressed wood from oil palm trunk. This paper will cover the background of compressed wood and the possibilities of producing compressed wood using oil palm trunk as a raw material.

Keywords: Compressed wood; Oil palm trunk; Steaming; Mechanical; Physical; Dimensional stability

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INTRODUCTION

The oil palm tree (*Elaeis guineensis*) is indigenous to the tropical forests in West Africa. The oil palm tree was introduced to the Bogor Botanical Garden of Indonesia in 1848 before it was first planted in Malaysia as an ornamental plant in 1871 (Basiron *et al.* 2000). The plantation area of oil palm tree in Malaysia has been rapidly increasing on a yearly basis, especially between 1975 and 2010, as illustrated in Fig. 1.

The oil palm tree has become one of the most valuable commercial cash crops in Malaysia. A report on the performance of the Malaysian oil palm industry showed that the oil palm planting area increased substantially from 3.37 x 10^6 ha in 2000 to 4.05 x 10^6 ha in 2005. In 2010 the total oil palm planted area was 4.85 million hectares (Fig. 1). With such a large area of plantation, the amount of planting of oil palm is creating a significant biomass that can be converted into a value-added product.

People working in the wood industry in Malaysia struggle to obtain sufficient raw materials at a competitive price. Oil palm trunk (OPT) is abundantly available, and it is a less expensive lignocellulosic raw material as compared to wood. Using oil palm biomass as a raw material to produce value-added products will not only reduce the overall costs of production but will also increase economic returns.

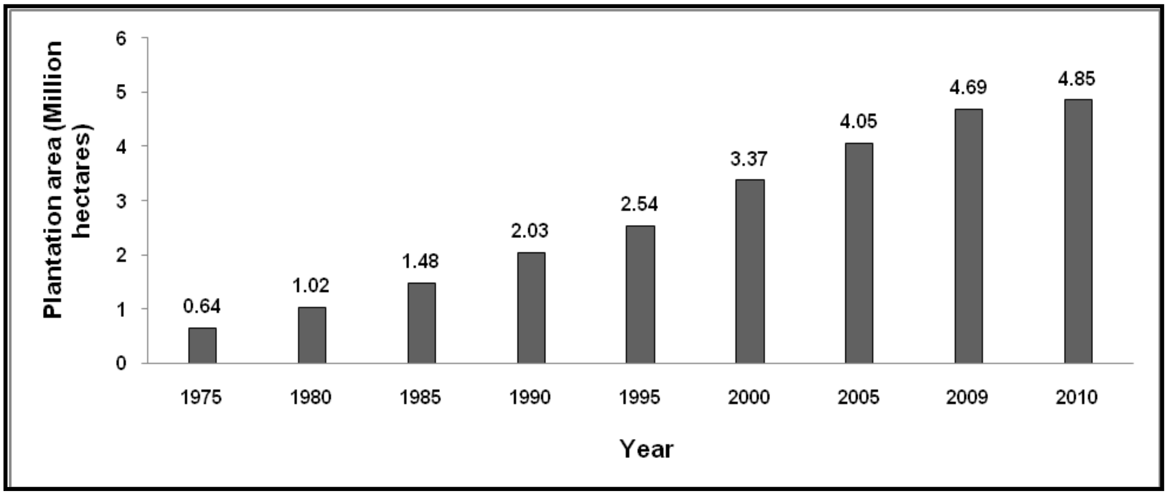

Fig. 1. Plantation area of oil palm in Malaysia from 1975 to 2010 (Malaysian Oil Palm Statistic 2010)

In fact, veneer and plywood manufacturers have focused heavily on the use of OPT as a raw material in different applications. Oil palm trunk (OPT) can also be used in laminated products, such as laminated veneer lumber and both interior and exterior plywood (Nordin *et al.* 2004; Sulaiman *et al.* 2008). Compressed oil palm, as a non-wood resource, could have the potential to be used as construction material in various applications. Therefore, the objective of this work is to review evidence regarding the potential of oil palm trunk biomass to be used in value-added compressed wood.

Compression of wood is a process to increase the wood's density by modifying the cell structure using either physical or mechanical methods (Wong *et al.* 2008). Wood compression techniques have been applied to solid wood, wood chips, and wood veneer in previous works that involved employing platen compression (Bekhta *et al.* 2009; Unsal, *et al.* 2009; Adachi *et al.* 2004). One of the main advantages of the compression of wood and wood-based materials is the reduction of adhesive consumption as a result of having a densified, smooth surface on the final product (Adachi *et al.* 2004; Bekhta and Marutzky 2007).

OIL PALM AS RENEWABLE RESOURCE

Development of the oil palm plantation in Malaysia had grown increasingly up until the end of the twentieth century. Malaysia and Indonesia have become dominant in the trade and have begun producing a great deal of palm oil and palm kernel oil. Malaysia and Indonesia also now have very efficient supply chains and have built a reputation for being reliable partners in trade. The development of the palm oil industry began in smallholder plots and farms and was initially only used for the farmer's domestic purposes or sold locally (Ernst and Fairhust 1999). It is estimated that worldwide production rose from 21 million tons of palm oil in 2000 to 45 million tons of palm oil in

2009. Most of this increase can be attributed to production in Malaysia and Indonesia, and some to smaller Asian producers (Malaysian Palm Oil Board Statistics 2009).

Almost 80% of the world oil palm plantation is centered at Southeast Asia, with most of it occurring in Malaysia and Indonesia. Additionally, there are 260,000 hectares planted in Thailand, with smaller areas in the Philippines and some recent plantings in Cambodia and Myanmar (Ernst and Fairhust 1999). Table 1 illustrates the total export of oil palm products in Malaysia increased from year 2009 to 2010. As can be seen in Table 1, the total exports of oil palm products, including palm oil, palm kernel oil, palm kernel cake, oleochemicals, biodiesel, and finished products increased from 22.43 million tonnes in 2009 to 23.06 million tonnes in 2010 because of higher export prices of oil palm products.

Table 1. Total Export of Oil Palm Products in Malaysia, 2009 to 2010

	2009	**2010**
Palm oil	15,880,744	16,664,068
Palm kernel oil	1,117,478	1,163,586
Palm kernel cake	2,381,571	2,443,383
Oleochemicals	2,174,667	2,223,668
Biodiesel	227,457	89,609
Finished product	580,233	409,373
Other palm products	64,898	66,343
Total exports (Tonnes)	**22,427,050**	**23,060,031**
Source: Malaysian Oil Palm Statistic 2010		

As the world's major palm oil producer, as shown in Fig. 2, Southeast Asia has greater productivity than the other major producing regions.

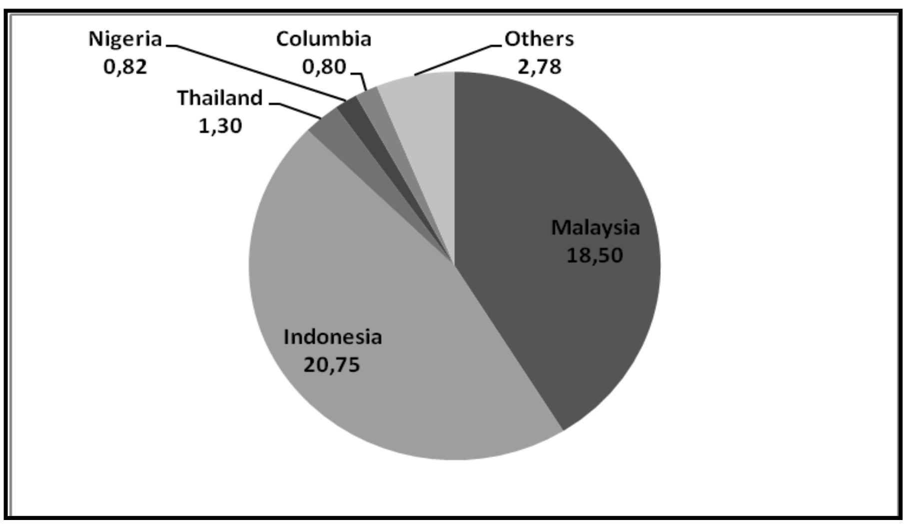

Fig. 2. World major producers of palm oil 2009/2010 ('000 tonnes) (Forest Agriculture Service 2009)

There are a few factors that led to the expansion of the harvesting area in Southeast Asia. One factor is the increase in the consumption of dietary oils and fats in China and India. This factor strengthened the market prices of palm oil and kernel oil.

This has encouraged investors to develop plantations on the large areas of suitable land found in Peninsular Malaysia and the islands of Sumatra in Indonesia and Borneo, where certain parts belong to Malaysia (*e.g.*, Sabah and Sarawak) and certain parts belong to Indonesia (*e.g.*, Kalimantan) (Ernst and Fairhust 1999; Ratnasingam *et al.* 2008).

Oil palm cultivation and processing, similar to other agricultural and industrial activities, are regulated by environmental legislation aimed at conserving and protecting the natural environment. These rules and regulations play a significant role in minimizing the degradation of the soil, water, and the atmospheric environment (Ernst and Fairhust 1999). The oil palm industry is currently producing the largest amount of biomass in Malaysia with 85.5% of oil palm plantations in Malaysia, as shown in Fig. 3 (Shuit *et al.* 2009). As the second largest oil palm plantation country after Indonesia, Malaysia produces a large amount of residues due to increasing global demand for palm oil. With such a large area of oil palm plantations, an abundant oil palm biomass will be produced over the years due to replanting of the oil palm trees when the trees mature. Of course, if this biomass were not managed in the correct way, the environment will be polluted. Therefore, research on oil palm biomass has begun to help reduce oil palm biomass waste and at the same time, increase the economic return for the country.

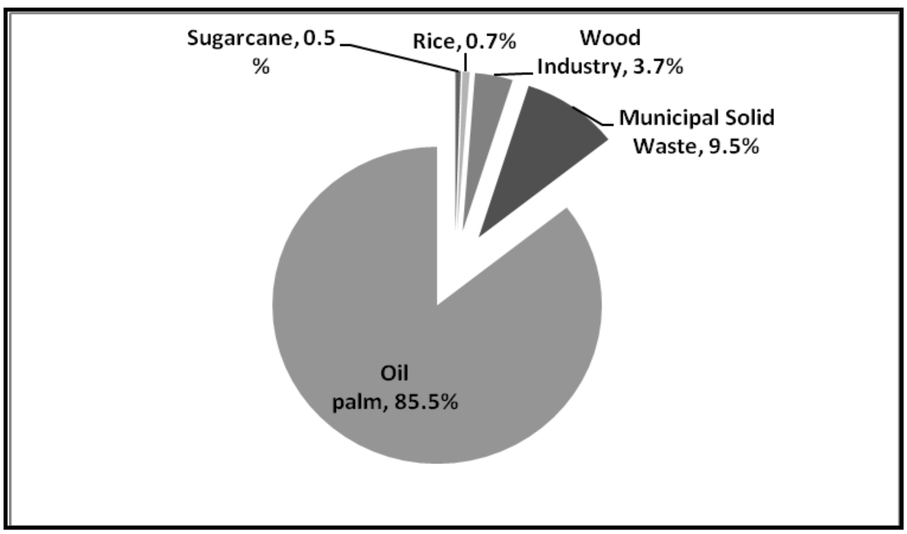

Fig. 3. Biomass produced from different industry in Malaysia (Shuit *et al.* 2009)

Oil Palm Biomass

Biomass refers to any organic plant product that has general uses. Each year, the oil palm industry in Malaysia generates more than 30 million tons of biomass in the form of empty fruit bunches, oil palm trunks, and oil palm fronds. Oil palm biomass of trunks, fronds, empty fruit bunches, fiber, shell, and effluent are obtained in two different situations. Trunks and fronds are obtained from oil palm growing on plantations, and empty fruit bunches, fiber, shell, and effluent are obtained from oil palm processing (Hassan *et al.* 1997).

Oil palm trunks are available only when the economic lifespan of the palm is reached at the time of replanting. The average age of replanting is approximately 25 years. The main economic criteria for felling are the height of the palm, reaching 13 m and above, and the annual yield of bunches falling below 10 to 12 t/ha. During replanting, the diameter of felled trunk is around 45 cm to 65 cm, measured at breast height. Oil palm fronds are obtained during replanting at either harvesting or pruning time. Normally, at the time of replanting, the crown yields approximately 115 kg/palm of dry fronds. On an annual basis, 24 fronds are pruned, and the weight of fronds varies considerably with the ages of the palms, with an average annual pruning yield of 82.5 kg of fronds/palm/year (Chan *et al.* 1980).

Over the years, the oil palm industry has been very responsible, and all the co-products have gradually been utilized. The utilization of the various co-products through nutrient recycling in the fields has reduced the environmental impact, paving the way toward a zero-waste policy. In 1990, there was a further move to improve the use of these co-products through the development of value-added products (Gurmit *et al.* 1999).

There are many uses of potential value-added products made from oil palm trunk such as particleboard, laminated board, plywood, fiberboard, and furniture. Oil palm trunk can also be used for making paper. It can also be used as a nutrient in plantations, as erosion control measure, and as animal feed (Gurmit *et al.* 1999; Sulaiman *et al.* 2008).

The Anatomy of Oil Palm Trunk

The oil palm tree is a non-wood tree. Oil palm is a monocotyledonous species and does not have cambium, secondary growth, growth rings, ray cells, sapwood, and heartwood or branches and knots. The anatomical structure of oil palm consists of vascular bundles and parenchyma cells, in contrast to hardwoods and softwoods, for which the cells consist of mostly fibers, tracheids, vessels parenchyma, and ray parenchyma cells. The chemical composition of oil palm trunk differs from hardwood/softwood species, with alterations in cellulose, hemicellulose, and lignin content (Akmar and Kennedy 2001).

Growth in stem diameter results from the overall cell division and cell enlargement in the parenchymatous ground tissues, together with the enlargement of the fibres of the vascular bundles. There are three main parts. First is the cortex, second the peripheral region, and last the central zone in the cross section of the oil palm trunk (Killmann and Lim 1985; Corley and Tinker 2003).

After 25 years, oil palm is usually replanted. At replanting age, the oil palm trunk has a height that ranges from 7 to 13 m and a diameter between 45 and 65 cm, measured 1.5 m above ground level. The trunk tapers towards the crowns which generally produce about 41 fronds when mature. The anatomical features of cross-section of oil palm trunk described based on the work by Killmann and Lim (1985) are shown in Fig. 4.

(a) Cortex

The cortex is a narrow zone that is approximately 1.5 to 3.5 cm wide and makes up the outer part of the trunk (Fig. 4). It is largely composed of ground tissue parenchyma with numerous longitudinal fibrous strands of small and irregular shaped fibrous strands and vascular bundles (Lim and Khoo 1986).

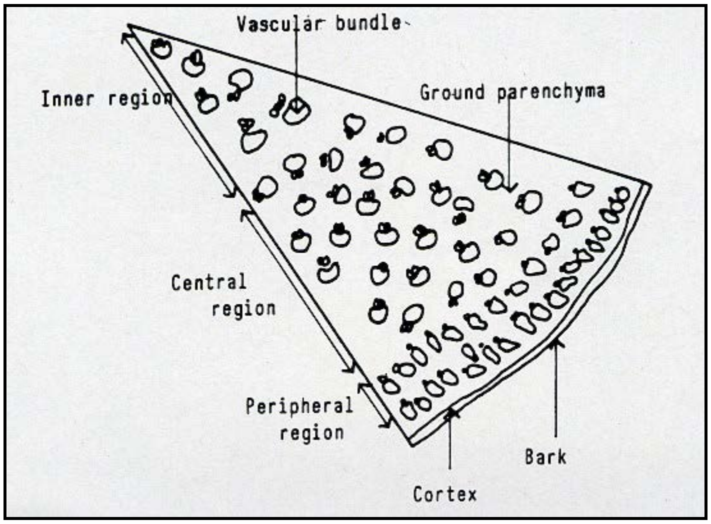

Fig. 4. Cross-section of oil palm trunk (Killmann and Lim 1985)

(b) Periphery

The periphery is a region with narrow layers of parenchyma and crowded vascular bundles (Fig. 4) that provides the main mechanical support for the palm trunk. The peripheral region normally contains a large number of radially extended fibrous sheaths, thus providing the mechanical strength to the palm. This region makes up about 20% of the total area of the cross-section. The fibres have multi-layered secondary walls and increase in length from the periphery to the pith. The basal parts of the stem, being older normally have better developed secondary walls than do the top parts. The phloem cells, in single strand, are present between the xylem and fibre strands. According to Lim and Khoo (1986), the number of vascular bundles is about 87/cm^2 in the periphery region (Killman and Lim 1985).

(c) Central

The central zone makes up about 80% of the total area and is composed of slightly larger and widely scattered vascular bundles embedded in the thin-walled parenchymatous ground tissues (Fig. 4). Towards the core of the trunk the bundles increase in size and are more widely scattered. Lim and Khoo (1986) estimated that the number of vascular bundles is about 37/cm^2 at central region (Killmann and Lim 1985).

(d) Vascular bundles

Each vascular bundle is basically made up of a fibrous sheath, phloem cells, xylem, and parenchyma cells (Figs. 4 and 5). According to Lim and Khoo (1986), the number of vascular bundles per unit area decreases towards the inner zones and increases from the butt end to the top of the palm. The xylem is sheathed by parenchyma and contains mainly one or two wide vessels in the peripheral region or two to three vessels of similar width in the central and core region (Killman and Lim 1985).

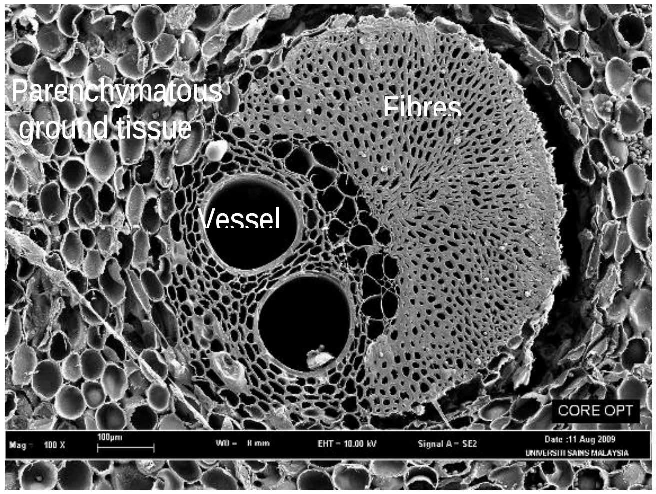

Fig. 5. Vascular bundles with vessels of oil palm trunk (Hashim *et al.* 2012)

(e) Parenchymatous tissue

The ground parenchymatous tissue consists mainly of thin-walled spherical cells, except in the area around the vascular bundles (Figs. 4 and 5). The walls are progressively thicker and darker from the inner to the outer region (Killman and Lim 1985).

In comparison with oil palm, a softwood species, *Picea abies* (Norway spruce) exhibits a different anatomy. Since it is a type of softwood, it consists of earlywood and latewood, which can clearly be observed visually. The latewood (LW) is denser than earlywood (EW), and when examined under a microscope, as shown in Fig. 6, the cells of dense latewood are seen to be very thick-walled with very small cell cavities, while those of earlywood have thin walls and large cell cavities. The tracheids are typically regularly ordered and almost perfectly rectangular in cross section.

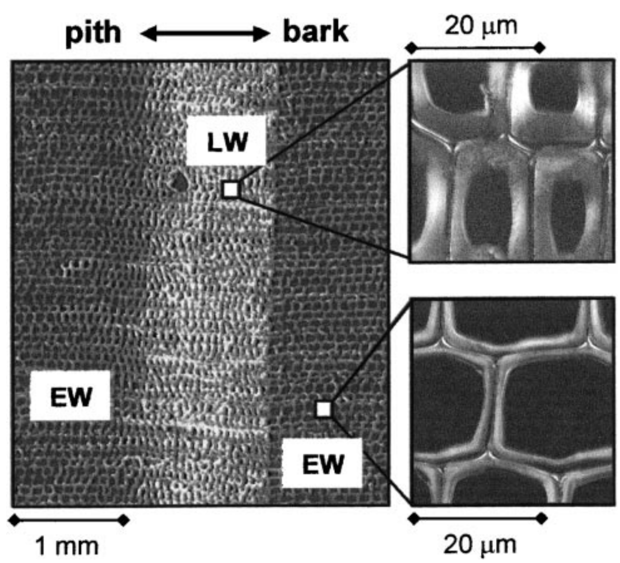

Fig. 6. Polarization microscopic image of a cross section of *Picea abies* (stem, mature wood). The direction of growth is from the left to the right, as denoted on the top of the figure. The right panel shows thick-walled late wood (LW) tracheids and thin walled early wood (EW) tracheids in greater magnification (Lichtenegger *et al.* 1999)

Chemical Composition of Oil Palm Tree

Oil palm is a lignocellulosic material that contains a high level of carbohydrates. These carbohydrates are mainly in the form of sugar-containing cellulose, starch, hemicelluloses, and lignin (Murai *et al.* 2009). Sulaiman *et al.* (2009) found that the chemical composition of oil palm biomass consists of high holocellulose, lignin, starch, and sugar contents that have been found to aid in the production of binderless panel. Starch contributes to interfacial adhesion when manufacturing binderless panels. Studies carried out by Hashim *et al.* (2011) found that, of all parts of the oil palm tree, the trunk contains the highest amount of starch and total sugar. Generally, holocellulose consists of hemicelluloses and cellulose. These two components are desirable in the production of binderless panel. Table 2 shows differences in starch content, sugar content, and types of sugar in different parts of an oil palm tree. Starch and sugar contents are highest in the core part of the oil palm trunk.

Table 2. Chemical Composition of Different Parts in Oil Palm Tree (Hashim *et al.* 2011)

Oil palm tree by parts	Starch (%)	Sugar composition (mg/ml)				Total sugar (mg/mL)	Total sugar using phenol sulfuric acid method (mg/mL)
		Glucose	Xylose	Arabinose	Fructose		
Bark	4.14 (0.30)[a]	3.53 (0.61)	6.55 (3.25)	1.15 (0.57)	0.22 (0.38)	11.42	13.67 (0.90)
Leaves	2.53 (0.12)	2.17 (0.17)	3.79 (3.72)	1.70 (0.69)	-	7.66	9.29 (0.39)
Fronds	3.10 (0.09)	5.31 (0.95)	6.50 (3.42)	1.33 (0.49)	-	13.14	14.29 (2.74)
Mid-part of trunk	12.19 (0.63)	5.97 (0.65)	6.61 (3.51)	1.09 (0.55)	-	13.67	14.45 (1.02)
Core part of trunk	17.17 (0.40)	6.55 (0.58)	6.20 (3.71)	1.31 (0.60)	0.04 (0.07)	14.06	16.56 (1.15)

[a] Values in parentheses are standard deviation

Starch content is also high in parenchyma cells. Xylose and glucose are the main sugar components in both tissues, indicating that the polysaccharide consists of xylan, starch, and cellulose. This causes fungi to grow rapidly on the surface of cross-sections of oil palm trunks.

Numerous chemical analyses have shown that oil palm trunks contain a considerable amount of starch. Extraction of starch from the trunks will not only contribute to economic return but will also diversify the use of starch-free fibers into many useful applications. The starch of the oil palm trunk is stored inside the parenchyma cells of the coarse vascular bundles, which contain a high percentage of lignin. Parenchymatous tissue with starch granules is generally present in the cells. These cells contribute to the improved interfacial adhesion that provides good bonding between the fibers. The starch granules fill up the voids in between the cells and aid in the interfacial adhesion between the fibers.

A study done by Normah *et al.* (1994) showed that starch content is variable, depending on the position along the trunk. The highest starch concentrations were found in the apical region of the trunk in young palms. It is likely that carbohydrate levels in all parts of the trunk will vary with age and condition of the palm. Samples taken closer to the trunk base contained more starch compared to the upper part of the trunk.

POTENTIAL OF OIL PALM TRUNK

The process of compressing wood could also be applied to oil palm (*Elaeis guineensis*) trunk, although this has not yet been reported in the literature. Oil palm has high density variability, especially between the inner and outer part of the trunk, which could result in some problems for its efficient utilization. This will subsequently affect most of the fundamental physical properties of the final product and could lead to undesired excessive shrinkage and swelling. It seems that compression could provide a potential solution to this problem by reducing its variability across the trunk of such species.

Manufacturing parameters such as pre-treatment, pressure, temperature, and chemical properties have been found to have an important influence on the properties of compressed wood (Shahbazi *et al.* 2005; Cai *et al.* 1992; Hsu *et al.* 1988; Hillis 1984). Therefore, determination of ideal parameters will be an important step towards finding the optimum manufacturing conditions for compressed oil palm trunk.

Since the supply of wood is limited, the compression method could be applied to oil palm trunk biomass. Oil palm trunk is not only abundant in this country but is also a cheap, environmentally friendly resource and can likely be converted into a value-added product such as compressed wood. The anatomy of oil palm trunk may differ from wood, but it could be effective for use as compressed wood with some modifications. Use of non-wood resources could overcome the issue of limited wood supply.

HISTORICAL BACKGROUND OF COMPRESSED WOOD

The compressed wood known by the trade name of Lignostone was first produced in Germany in 1930. There are two methods that have been established in the United States for production of compressed wood products, namely Compreg (Stamm and Seborg 1941) and Staypack (Seborg *et al.* 1962), both of which were developed at the Forest Products Laboratory in Madison.

Compreg is a resin-treated compressed wood that is produced by treating solid wood or veneer with water-soluble phenol formaldehyde resin and compressing it to the desired specific gravity and thickness (Kamke 2008). Two factors should be considered before making Compreg. First, the wood should be dried to avoid pre-cure, and second, the panels must be compressed under specific temperatures to cure the resin. In order to obtain the maximum dimensional stability of the Compreg, there are a few parameters that should be considered. The parameters are resin content, specific gravity, pressure, types of resin and its volatile contents, degree of pre-cure of the resin, the distribution of the resin throughout the structure, and the species of the wood (Kultikova 1999). Besides, Compreg can also be made from veneer (Seborg *et al.* 1962; Kultikova 1999). In terms of strength, the impact strength of Compreg is proportional to the increase in its specific gravity. Compreg is known to be more dimensionally stable than non-impregnated compressed wood (Kultikova 1999). A resin-treated compressed wood similar to Compreg has been made in Germany under the name Kunstharzchichtholz (Kollmann *et al.* 1975).

Staypack is not impregnated with resin because treatment with resins will result in hardening within the cell wall, which will cause the wood to become more brittle. The manufacturing process depends on the requirements of the final product. For example, if a tough final product is desired, wood should not be impregnated with a brittle polymer. The major problem of compressed solid wood is springback. Springback is recovery from compression when wood is exposed to moisture. Other than moisture absorption, released stresses after compression also contributes to springback of the wood. Springback, unlike actual swelling, is not reversible. This situation happens because of the internal buildup caused by the original compression released when the wood is softened (Kamke 2008). Seborg *et al.* (1962) found that removing the built up stresses will reduce the springback. This phenomenon happens because of slight flow of the cementing lignin between the fibers. Wood should be pressed under conditions that allow for sufficient flow of lignin to eliminate the springback effects (Kamke 2008). For a final specific gravity of 1.3, Staypack can be manufactured by using temperatures of the hot press ranging from 150 °C to 180 °C and pressures of 1,400 to 2,500 psi (Seborg *et al.* 1962; Rowell and Konkol 1987). Staypack should be cooled to 100 °C or less while under full pressure after manufacturing. Staypack should not be removed from the hot press before it is cooled in order to prevent minor springback. This is due to the thermoplastic nature of the lignin and because the moisture content of the wood is slightly decreased after compression compared to wood prior to pressing (Kollmann *et al.* 1975; Kamke 2006). A comparable study on improved dimensional stability by a post treatment above 180 ºC has been done by several authors (Inoue *et al.* 1993, Dwianto *et al.* 1996). The results indicated that the dimensional stability of wood is caused by increasing cross linkages (Navi and Girardet 2000) and relaxation of stored stresses by partial hydrolysis of hemicelluloses and degradation of lignin at elevated temperatures (Kawai *et al.* 1992). The strength properties of Staypak are generally comparable with Compreg, except that the impact strength is considerably higher, while the dimensional stability is decreased compared to Compreg (Rowell and Konkol 1987). The properties of Compreg and Staypack are described in Table 3.

PREVIOUS RESEARCH RELATED TO COMPRESSED WOOD

Dimensional stability is one of the major problems of compressed wood. Compressed wood may be utilized in high humidity environments due to the many uses of compressed wood in construction. When the compressed wood is exposed to high humidity or soaked in water, it will tend to exhibit springback. Therefore, during

Table 3. Properties of Compreg and Staypack (Rowell and Konkol 1987)

Property	Compreg	Staypack
Specific gravity	Usually 1.00 to 1.40	1.25 to 1.40
Equilibrium swelling and shrinking	1/4 to 1/3 that of normal wood at right angle to direction of compression, greater in direction of compression but very slow to attain	Same as normal wood at right angles to compression, greater in direction of compression but very slow to attain
Springback	Very small when properly made	Moderate when properly made
Decay and termite resistance	Considerably better than normal wood	Normal but decay occurs somewhat more slowly
Compressive strength	Increased considerably more than proportional to specific gravity increase	Increased about in proportion to specific gravity increase parallel to grain, increase more perpendicular to grain
Tensile strength	Increased less than proportional to specific gravity increase	Increased about in proportion to specific gravity increase
Flexural strength	Increased less than proportional to specific gravity increase parallel to grain, increased more perpendicular to grain	Increased proportional to specific gravity increase parallel to grain, increased more perpendicular to grain
Hardness	10 to 20 times that of normal wood	10 to 18 times that of normal wood
Impact strength toughness	1/2 to 3/4 of value for normal wood but very susceptible to the variables of manufacture	Same to somewhat greater than normal wood
Gluability	Same as normal wood after light sanding or in the case of thick stock, machining surfaces plane	Same as normal wood after light sanding, or in the case of thick stock, machining surfaces plane

production of compressed wood, the manufacturing conditions under which the recovery of the compressed wood is minimized must be utilized.

Numerous experimental studies of compressed wood have been carried out. A review article by Hillis (1984) examined stabilization of wood through a heating process. Various studies have been carried out to investigate the effect of steam pre-treatment on wood (Hsu *et al.* 1988; Inoue *et al.* 1993, 1996; Kawai *et al.* 1992). Hsu *et al.* (1988) introduced a steam pre-treatment process to produce a wood-based composite using aspen (*Populus tremuloides* Michx.) and pine (*Pinus contorta* Dougl.) with high dimensional stability. The results indicated that steam pre-treatment caused partial hydrolysis of hemicelluloses in both softwood and hardwood. Hence, this treatment increases the compressibility of wood. Several wood densification processes were developed to enhance its properties by using spruce and pine (Navi and Heger 2004), radiata pine (Kamke 2006), *Cryptomeria japonica* and *Pinus densiflora* (Inoue *et al.* 2008), and *Populus tremuloides* (Fang *et al.* 2012). There were few methods to increase wood density, *e.g.* by compressing wood to reduce void volume, impregnating the void volume with synthetic or natural polymers in fluid form, or by using a combination of compression and impregnation (Bustos *et al.* 2011). However, chemical impregnation affects natural characteristics of wood and is quite costly. Recent studies were done to improve the dimensional stability of compressed wood, which attempted the combined process of heat and steam (Higashihara *et al.* 2000; Navi and Heger 2004; Kamke 2006; Fukuta *et al.* 2008; Inoue *et al* 2008; Gabrielli and Kamke 2010). The tendency of internal stresses to build up in composites is reduced during hot pressing. Inoue *et al.* (1993) found that post-steaming the sample of compressed wood at 200 °C for 1 min or at 180 °C for 8 min resulted in almost complete fixation of the wood. The results showed that a slight decrement in modulus of elasticity (MOE) and modulus of rupture (MOR) replaced with a very significant increment in hardness.

Blomberg *et al.* (2005) reported that less softening of wood during compression resulted in lower strength at a given density after densification. This indicated that the relationship between strength properties and density diagnosed the damages of the cell walls due to densification.

A study done by Inoue *et al.* (1996) investigated the effect of pre-steaming and found that by increasing the temperature and pressing time, the degree of recovery decreased. Pre-steaming increased the compressibility of wood and at the same time reduced the amount of stored stress. Kawai *et al.* (1992) developed a new technique by producing laminated veneer lumber (LVL) using steam-injection pressing. Their results showed that if density is increased, MOE and MOR will also increase. Therefore, the dimensional stability of LVL can be improved. They have also demonstrated the mechanism responsible for the fixation of compressive set by steam pre-treatment (Kultikova 1999). Hypothetically, stress relaxation in microfibrils and relaxation in compressive set is affected by rapid hydrolysis of hemicelluloses and partial degradation of lignin. This includes reorientation in the crystalline region triggered by steam pre-treatment and partial hydrolysis of cellulose in either the amorphous or paracrystalline region (Kamke 2006).

Wong *et al.* (2008) found that after wood undergoes a steaming process, the hemicellulose and lignin are softened. When hemicellulose and lignin become soft, it is easier to compress the wood without causing any damage to the cell structure. Therefore, the compressibility of wood will be increased. Dwianto *et al.* (1996) found that steam acts by dissolving or altering (oxidizing and/or decomposing) extractives and other chemical constituents of the wood. Strength properties of compressed wood also depend on the steaming temperature. If the pre-steaming temperature is higher, a higher plastic strain area will develop. The pre-steaming temperature has effects on compressive deformation and thickness recovery. By applying a steaming process to the wood, the recovery of compressed wood is minimized. However, steaming above 100 °C will lead to a decrease in the strength properties. Generally, mechanical properties decay with higher steaming temperatures or longer treatment times. Long-term steaming at high temperatures will decrease the hardness of wood during treatment. Steaming optimizes the surface chemistry, but at the same time, strength properties will decrease with increasing treatment time. Generally, the decrease in strength values is proportional to the density decrement.

The effect of heat on the dimensional stability of compressed wood has also been evaluated. Tomme *et al.* (1998) investigated how to produce densified wood with stable deformation by utilizing thermo-hygromechanical treatment. Dwianto *et al.* (1996) found that preheating significantly influenced the permanent fixation. According to the results obtained, stresses stored in microfibrils and the matrix substances of the cells were released due to degradation. Therefore, this results in the permanent fixation of compressive deformation in wood (Kamke 2006).

Many researchers have studied the influence of high temperature and steam pressure on wood (Price 1976; Geimer *et al.* 1985; Kamke and Casey 1988; Kosikova *et al.* 1993; Ebringerova *et al.* 1993; Gardner *et al.* 1993). They found that the conditions under which the material was processed influenced the stiffness and strength of compressed wood, which either can be increased or decreased (Kultikova 1999). Kosikova *et al.* (1993) and Ebringerova *et al.* (1993) performed a study to investigate the effect of steam treatment on structural changes of the lignin-polysaccharide complex of three different species of wood namely, beech (*Fagus sylvatica*), aspen (*Populus tremuloides*), and spruce (*Picea abies*). These trees were subjected to multiple steaming conditions. These conditions were heating with steam under a pressure of approximately 4.3 MPa at 255 °C for 55 min, heating with steam at 200 °C for 10 min, heating with steam at 200 °C for 2 min under steam explosion conditions (4.3 MPa), and heating with steam at 115 °C for 5 min. Infrared spectroscopy was utilized to characterize the changes in wood polymer structure, and it was clear that there was an increase in cellulose crystallinity in the wood samples that had been steamed mainly under steam explosion conditions. The effects of steam pre-treatment were splitting of lignin-hemicellulose linkages in hardwoods and spruce and hydrogen bond destruction, resulting in increased of crystallinity.

Gardner *et al.* (1993) reviewed the changes in the polymer structure of wood flakes under hot-pressing conditions. The elastic modulus has been found to increase when the cellulose crystallinity increased with heat and steam treatment. The crystallinity increase is attributed to the transition of amorphous polymers from the glassy to the rubbery state. This is due to the increased mobility of lignin and hemicelluloses, which allowed reorientation and crystallization of the cellulose microfibrils.

Compressing wood process

There are two conditions of manufacturing compressed wood, namely the closed and open systems. Closed system processing is applied on wood by softening, compressing, and fixing wood in one step in a closed system with subsequent cooling in the compressed state. The wood is compressed in a hot-press equipped with a sealing to prevent the moisture from escaping. The treatment is using the intrinsic moisture in the wood to create a steam pressure. On the other hand, in the case of an open system, wood is treated without sealing under identical conditions (Morsig 2000).

Three main processes used to compress wood are the plasticizing process, the compression process, and the fixation process. These processes are referred to as the high temperature and the high steam method (Hata 1994). In the plasticizing process, wood is steamed at atmospheric pressure or at low gage pressure, soaked in boiling or nearly boiling water, or moistened and heated by microwave. Rowell and Konkol (1987) found that wood with a 20% to 25% moisture content needed to be heated without losing moisture. This is because heat and moisture must be applied at lower moisture content. As a solution, the recommended plasticizing processes involve steaming or boiling for approximately 30 min/cm of thickness for wood with lower moisture content and steaming or boiling for approximately 15 min/cm thickness for wood with 20% to 25% moisture content.

The cellular structure of wood changes permanently during densification and subsequently results in a material with new properties. This happens due to the compression and fixation processes. The amount and type of cellular collapse are the major factors influencing physical and mechanical behaviors of compressed wood. High temperature and steam pressure change the cellular structure of wood during the compression process. Dimensional stability and strength of compressed wood is highly influenced by structural modifications of the cell walls resulting from applied compressive strains. The mechanical properties of cellular materials in transverse compression are highly non-linear due to the collapse of the cellular structure.

Cellular collapse occurs, dependent on the nature of the cell wall material and the test conditions. According to Wolcott (1989), there are three ways in which cellular collapse can occur: plastic yielding, elastic buckling, and brittle crushing.

- Plastic yielding is the situation in which the polymer is in transition between glassy and rubbery phases. This will result in permanent deformation remaining after the load is removed.
- Elastic buckling occurs when the polymers of the cell wall are in the rubbery phase. This will result in certain recovery of the deformation after removal of the load.
- Brittle crushing happens when the polymer is in the glassy phase.

The performance of the resulting product is also influenced by the parameters of the compression process (Kultikova 1999).

Application of Compressed Wood

Compressed wood is used in many industrial applications because its strength properties are high and comparable to other materials available in the market. Compreg is widely used in aircraft materials such as bolts in connector plates because of its good specific strength. It is also useful for aluminum drawing and forming dies, drilling jigs, and jigs for holding parts in place while welding. Due to Compreg's excellent strength properties, dimensional stability, low thermal conductivity, and ease of fabrication, it has also been used in silent gears and pulleys (Rowell and Konkol 1987).

Rowell (1975) found that Staypak is not as water resistant as Compreg, so it is not suitable to use for water resistance purposes. The advantages of Staypack are its high tensile and flexural strength properties. Staypak is typically used in connector plates, propeller and picker sticks, tool handles, and in forming dies and shuttles for weaving. Staypak is widely used in tools and materials that require high impact strength.

CONCLUSIONS

The stabilization of compressed wood is crucial for its applications. Therefore, various wood treatments have been carried out in order to meet the required strength properties for certain applications of compressed wood. Many studies have been undertaken previously on compressed wood, but there is no information yet on how to make compressed wood using oil palm trunk as a raw material, or even on the properties of compressed oil palm. Therefore, a study is needed to investigate the possibility for making compressed wood from oil palm trunk, which is considered to be a plantation waste product. Compressed oil palm trunk is likely to be useful for flooring and other structural applications for buildings. Malaysia hopes to generate additional income from oil palm plantations by using oil palm trunk as a raw material. At the end of their commercial use for palm oil, trunks are typically left to rot, which has created a problem for plantation reestablishment. By converting oil palm trunk to compressed oil palm, a new product is created from oil palm waste, which at the same time will minimize the oil palm wastage and reduce the demand for wood.

The outcomes of this project will have a large direct impact on the Malaysian timber and wood-based industries, in addition to having a more global impact. Dissemination of this new technology will be done when this research is completed. The development of technology from the formulation and processing techniques will benefit wood-based industries. Compressed oil palm has the potential for use in various construction applications.

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