Effect of Steaming on Some Properties of Compressed Oil Palm Trunk Lumber

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Compressed lumber is considered to be a superior structural material due to its uniform properties and higher strength than other solid timbers. This study presents the effect of steaming on some properties of compressed lumber of oil palm (*Elaeis guineensis*) trunks (OPT). The specimens were steamed at a temperature of 130 °C for 2 hours before being compressed in a hot press and evaluated for their physical and mechanical properties. Compressed OPT without steaming was used as a comparison sample to compare the effect of steaming on compressed OPT. The average modulus of rupture of steamed compressed OPT samples was 31.36 MPa, which was 8.7% higher than the compressed OPT without steaming samples. The modulus of elasticity was determined to be 8919 MPa, 9.9% higher than the compressed OPT samples. Steaming enhanced the dimensional properties of the samples. Thickness swelling and water absorption of the steamed compressed OPT samples were 6.57% and 33.84%, respectively, lower than those of the samples without steaming. Some other properties such as compression strength, dynamic bending strength, and the compression and recovery ratios were also evaluated. Scanning electron micrographs taken from the cross section of the samples showed a clear difference between the compressed and uncompressed oil palm.

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

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INTRODUCTION

The oil palm tree is one of the most economical agricultural crops in Malaysia. It belongs to the species *Elaeis guineensis* under the family Palmaceae and originated in the tropical forests of West Africa (Basiron *et al.* 2000). In 2010, the total area of oil palm plantations in Malaysia was 4.85 million ha, and it is expected that this resource will increase in coming years (Malaysia Palm Oil Board Statistic 2010). Oil palm trees have an average economic life of about 25 years, and it is estimated that about 7 million metric tons of oil palm trunks are harvested annually; the land is replanted as new trees (Razak *et al.* 2008).

Although oil palm trees have enormous potential for use as raw material for different applications including value-added panels, composite panels, and structural members, the majority of the waste material from harvesting sites is mostly either burned or landfilled. Such practice is having a significant adverse impact on the environment. Considering the fact that biomass from oil palm trees is expected to double in the near future, it would bring a beneficial economic return to Malaysia if this material were efficiently used (Sulaiman *et al.* 2009). Although many studies have reported on the use of oil palm trunks for laminated veneer (LVL), pulp and paper, and different types of composites (Dahlan 2000), very limited information is available on the use of oil palm for compressed lumber (Salim *et al.* 2012)

The concept of wood densification dates back to the early 1400s (Seborg *et al.* 1962) and is used for strength enhancement. Properties of compressed lumber from different species have been investigated in past studies (Hsu *et al.* 1988; Inoue *et al.* 1993a, 1996; Kawai *et al.* 1992). A study showed that the adhesives consumption in plywood produced from compressed veneer was reduced significantly (Bekhta *et al.* 2009). Wong *et al.* (2008) investigated using steaming for chemical modification of wood. It was concluded that steaming makes the wood more flexible as a result of the softening of lignin and hemicelluloses in the cell wall. With limited research on the properties of compressed wood, Jenning (1993) evaluated the shear strength of compressed yellow poplar as a function of various types of adhesives. It was found that compressed specimens bonded using urea formaldehyde and phenol formaldehyde had relatively similar shear strength characteristics. Currently there is no information about the properties of steam-compressed oil palm trunk lumber; therefore, the objective of this study was to evaluate both the mechanical and physical properties of such samples to provide preliminary data. Compressed oil palm trunk lumber can thereafter be used for different applications more effectively with a better understanding of its behavior.

MATERIAL AND METHODS

Sample Preparation

Oil palm trunks of approximately 28 years old were obtained from a local plantation in Northern Malaysia. After felling, the trunks were immediately cut into small pieces with dimensions of 200 mm x 200 mm x 40 mm in a tangential direction. The samples were wrapped in a plastic bag and kept in a freezer until testing to avoid contamination before use. A steaming process was carried out in a closed chamber using an autoclave machine at a temperature of 130 °C. After steaming, the samples were dried in an oven at 50 °C to reduce the high water content in the oil palm trunk samples during the compression process. A low drying temperature was used to prevent the oil palm samples from warping. Ten replicates of compressed OPT were produced. The compressed OPT was hot pressed using a laboratory Molding Test Press, Model Fabricate GT-7014-A30, for 60 min at 200 °C and a pressure of 11.16 MPa (Salim *et al*. 2012). Compressed OPT without steaming treatment was produced to compare the effect of steaming to the compressed OPT. Compressed OPT without steaming will be coded as “compressed OPT” while compressed OPT with steaming will be coded as “steamed compressed OPT”. All the compressed OPT made were then conditioned in a conditioning room at 21 °C and a relative humidity of 65% before cutting the samples.

Moisture Content and Density

Samples were cut into a size of 50 mm x 50 mm x 100 mm for moisture content and density testing. The moisture content of the compressed lumber was determined based on the oven-dried weight. The densities were determined based on the current weights and current volumes of the samples (Sulaiman *et al*. 2009).

Thickness Swelling and Water Absorption

Thickness swelling and water absorption testing was carried out with samples of size 50 mm x 50 mm x 100 mm. The samples were immersed in water at room temperature and were measured after 24 h until the sample weights were constant. Thickness swelling and water absorption of the samples were expressed as a percentage of the initial thickness and weight of the sample before soaking.

Determination of Compression Ratio

The samples of dimensions 50 mm x 50 mm x 100 mm were used to measure the compression ratio. The compression ratio was calculated according Equation 1,

$$\text{Compression ratio} = [(T_1 - T_0)/ T_1] \times 100 \tag{1}$$

where T_1 is the thickness before compression and T_0 is the thickness after compression.

Determination of Recovery Ratio

Samples of dimensions 50 mm x 50 mm x 100 mm were used to measure the recovery ratio. The samples were boiled in boiling water for 2 h and the thickness of each sample was measured at four points midway along each side 1 cm from the edge before and after they were boiled into boiling water (Welzbacher *et al*. 2008; Inoue *et al.* 1993). Recovery ratio was evaluated according to the below equation,

$$\text{Recovery ratio} = [(T_{r1} - T_1) / T_0] \times 100 \tag{2}$$

where T_{r1} is the thickness after recovery, T_1 is the thickness before compression, and T_0 is the thickness after compression.

Static Bending

A static bending test was done according to ASTM D 143-94 using an Instron Machine model 5582. The size of the samples was 25 mm x 200 mm and the span length was 170 mm. The load was applied approximately 1.3 mm/min at a mean deformation speed from the surface of the test piece and the maximum load (P) was measured.

Dynamic Bending

A dynamic bending test was done according to ASTM D 143-94 using an Instron 5584 universal testing machine model 5582. The size of the samples was 25 mm x 200 mm with a span length of 170 mm. The load was applied approximately 1.3 mm/min at a mean deformation speed from the surface of the test piece. The impact machine used incremental drops of a hammer to perform the test. The weight of the hammer was 2.5 kg. The first drop started from 10 cm, after which the drops were increased in 10 cm increments until a height of 40 cm was reached.

Compression Strength

Compression strength testing was done according to ASTM D 143-94 using an Instron machine model 5582. The size of the samples was 25 mm x 100 mm. The load was applied approximately 0.078 mm/min at a mean deformation speed from the surface of the test piece and the maximum load (P) was measured.

Field Emission Scanning Electron Microscopy (FESEM)

Field emission scanning electron microscopy (FESEM) was used to characterize the morphology of the compressed oil palm trunk samples and the condition of their cells before and after compression. Micrographs were taken from the cross section of the samples. The samples were coated with gold using an ion sputter coater (Polaron SC515, Fisons Instruments, UK). A Scanning Electron Microscope LEO Supra 50 Vp, Field Emission SEM, Carl- Zeiss SMT, Oberkochen, Germany was used for microscopic study.

RESULTS AND DISCUSSION

Moisture Content and Density

Results of the average moisture content, density, compression ratio, and recovery ratio of the compressed lumber from oil palm trunk are presented in Table 1. The average value of moisture content for the steamed compressed OPT samples was 4.31% and for the compressed OPT samples the average was 5.19%. The moisture content of steamed compressed OPT and compressed OPT are low compared to solid OPT and solid rubberwood. This may be due to the compression process at a high temperature for 60 min.

Table 1. Moisture Content and Density of Compressed Oil Palm Trunk

	Moisture Content (%)	Density (g/cm^3)	Compression Ratio (%)	Recovery Ratio (%)
Steamed Compressed OPT	4.31 (0.32)[a]	0.76 (0.04)	77.16 (0.87)	1.75 (0.22)
Compressed OPT	5.19 (0.09)	0.69 (0.01)	76.98 (0.56)	2.41 (0.42)
Solid OPT*	9.74	0.43	-	-
Solid Rubberwood*	9.71	0.62	-	-

[a] Value in parentheses are standard deviation *Sulaiman *et al.* 2009

There are hydroxyl groups in hemicelluloses that can absorb water. Steaming allows OPT to undergo some modification and subsequently make a change to the chemical composition of the OPT structure and degrade the hydroxyl groups. This is due to hemicellulose being very sensitive to temperature. It can thermally degrade at a lower temperature compared to cellulose (Wikberg and Maunu 2004; Boonstra *et al.* 1998). Thus, the fact that the steamed compressed OPT had a lower moisture content than the compressed OPT was attributed to the degradation of hemicellulose during steaming.

The equilibrium moisture content (EMC) decreased due to heat treatment. Tiemann (1920) reported that the EMC of wood will drop due to drying at high temperature. The EMC of wood reaches a saturated point when it is no longer gaining or losing moisture; thus, dropping the EMC will decrease the moisture content. Decreasing the EMC will improve the dimensional stability (Kollmann *et al.* 1975). As a result, the steamed compressed OPT samples had a low moisture content compared to the compressed OPT samples. This is because during steaming, the samples exposed to high temperature subsequently experienced a decreasing EMC value. In addition, for the samples that were compressed at high temperature, the moisture was evaporated by the heat during its manufacturing process (Sulaiman *et al.* 2009).

The densities of the steamed compressed OPT and the compressed OPT were 0.76 g/cm^3 and 0.69 g/cm^3, respectively. A study by Sulaiman (2009) found the density of solid oil palm trunk to be 0.43 g/cm^3. Both the steamed compressed OPT and the compressed OPT showed an increasing density after being converted into compressed OPT as both underwent hot pressing during the compression process. This will result in a reduction of the total volume of the samples. This volume reduction will cause an increase in density (Sulaiman *et al.* 2009). High density will produce good properties in the final product.

Thickness Swelling and Water Absorption

Figures 1 and 2 show the thickness swelling and water absorption behaviors of the steamed compressed OPT and the compressed OPT.

Dimensional stability in terms of thickness swelling and water absorption is one of the major problems of compressed wood. Compressed wood may be utilized in high humidity environments, making possible many uses of it in construction. When compressed wood is exposed to high humidity or soaked in water, it tends to exhibit springback. Tomme *et al.* (1998) utilized thermo-hygromechanical treatment to stabilize deformation in making compressed wood. As shown in Fig. 1 and Fig. 2, steamed compressed OPT had good dimensional stability. This is probably due to the manufacturing process of compressed OPT, which included steaming and compression at high temperature. Dwianto *et al.* (1998) found that preheating significantly influenced the permanent fixation. Permanent fixation would improve the dimensional stability of compressed OPT. Steamed compressed OPT had low thickness swelling compared to the compressed OPT sample, as shown in Fig. 1. Thickness swelling and water absorption values increased with immersion time of the samples and then finally stabilized. Compressed OPT is subject to reversible and irreversible swelling phenomena. The reversible swelling is due to the hygroscopic nature of wood, while irreversible swelling is due to the springback of compressed (densified) wood and the breakage of adhesive bonds between the wood particles (Hsu *et al.* 1988).

In wood composites, irreversible swelling is much more likely than reversible swelling. This is because the wood is being compressed in the thickness direction during pressing. Hence, it induces internal stress within and between the wood particles. When a pressed board was immersed in water or exposed to high relative humidity, both swelling and moisture plasticization occurred. This allows the internal stresses within the wood and between the wood particles from absorbed water in the cell walls to be relieved (Hsu *et al.* 1998).

The percentage of water absorption of the steamed compressed OPT was lower than the compressed OPT, as indicated in Fig. 2. This showed that steamed samples absorbed less water than non-steamed samples. This is probably due to changing of the hydroxyl group arrangement in the wood chemical composition. The compressed OPT samples did not undergo the steaming process, so degradation of hemicelluloses did not occur. Hemicellulose is more hygroscopic and has a more non-arrangement hydroxyl group structure compared to cellulose and lignin. Meanwhile, cellulose and lignin have minor contributions in hygroscopic properties (Khalil *et al.* 2007). The degradation of hemicelluloses in the steamed samples caused the water absorption to be lower.

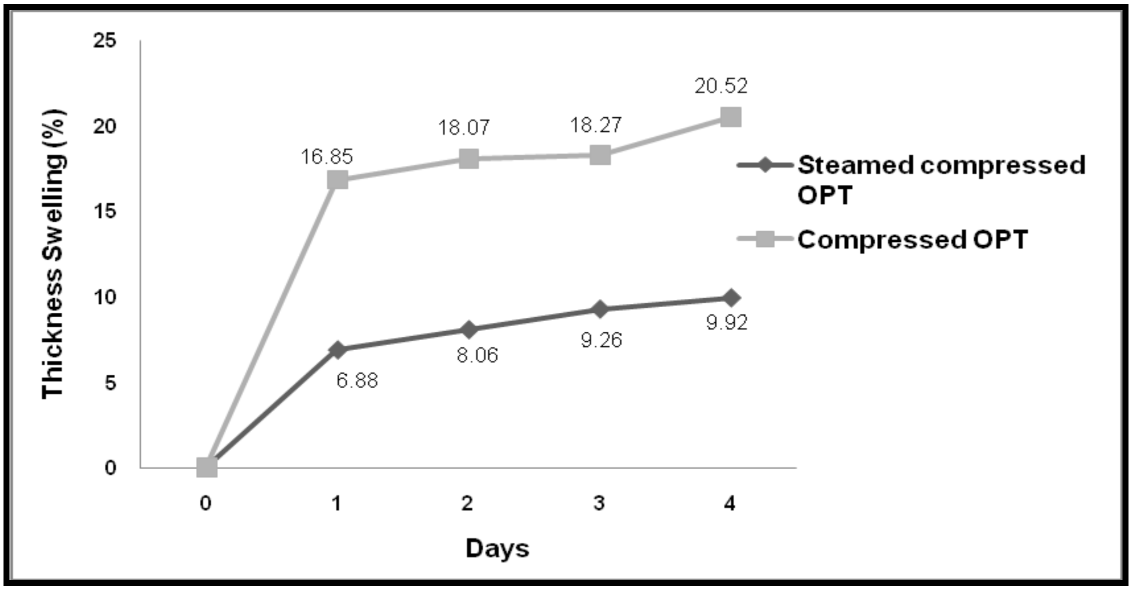


Fig. 1. Thickness swelling of the samples

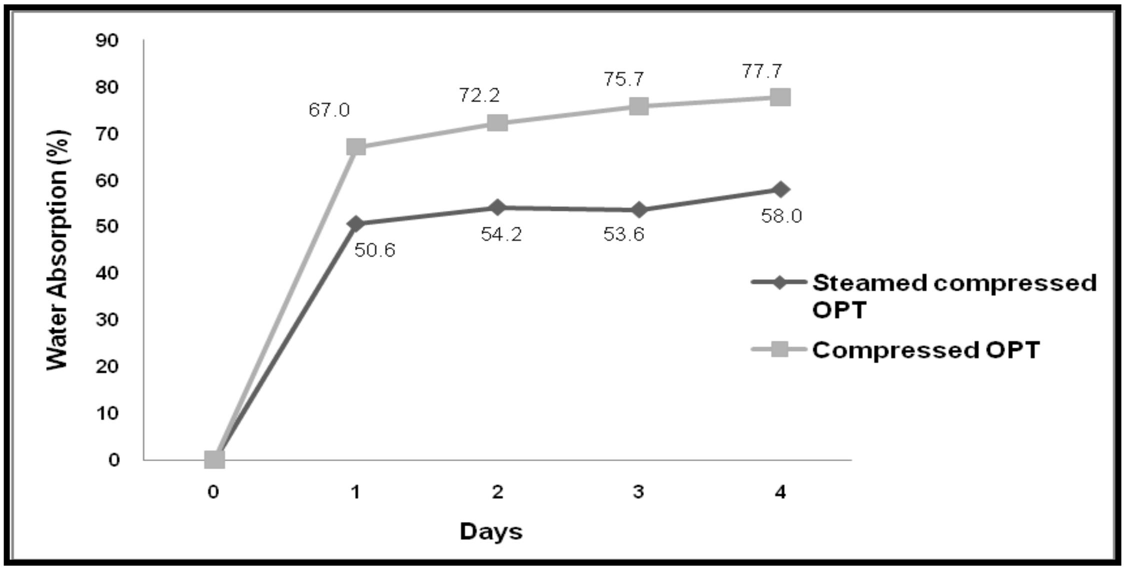


Fig. 2. Water absorption of the samples

A study performed by Hashim *et al.* (2011) found that the thickness swelling and water absorption of binderless board from oil palm trunk ranged from 20% and 130%, respectively. In comparison to the graph in Fig. 1, Fig. 2 shows an improvement in thickness swelling and water absorption after the oil palm trunk was converted into compressed OPT.

Compression Ratio and Recovery Ratio

The compression ratios for steamed compressed OPT and the compressed OPT were 77.16% and 76.98%, respectively. A higher compression ratio will result in higher sample density (Welzbacher *et al.* 2008). This can be explained as a consequence of the softening of solid wood at the elevated temperature (Fengel and Wegener 1984). Ohtani *et al.* (2002) reviewed that the shear strength of compressed sugi improved with an increase in density. The bending strength and Young's modulus also improved with an increase in compression ratio or density.

The recovery ratio is the percentage spring back of the sample after compression. The spring back of compressed wood is caused by internal stresses. The internal stresses will result in excessive thickness swelling when samples are exposed to moisture. Steaming is believed to reduce the spring back due to the hydrolysis of hemicelluloses and consequently will increase the compressibility of wood (Hsu *et al.* 1988). The recovery ratios of the steamed compressed OPT and the compressed OPT were 1.75% and 2.41%, respectively. Generally, a panel with a low value of recovery ratio is a panel that has good dimensional stability. A low value of recovery ratio means that the tendency of internal stress to build up in a panel during hot pressing was minimal. The steamed compressed OPT had a lower recovery ratio than the compressed OPT. This is because steamed compressed OPT underwent steaming before being compressed. During the steaming process, the hemicelluloses could be hydrolyzed which would subsequently increase the compressibility and reduce the amount of stored stress due to the viscous flow of wood substances (Hsu *et al.* 1988).

Static Bending

Figures 3 and 4 show the modulus of rupture (MOR) and modulus of elasticity (MOE) of the steamed compressed OPT and the compressed OPT. The Modulus of rupture (MOR) measured the maximum bending strength or maximum fiber strength before failure.

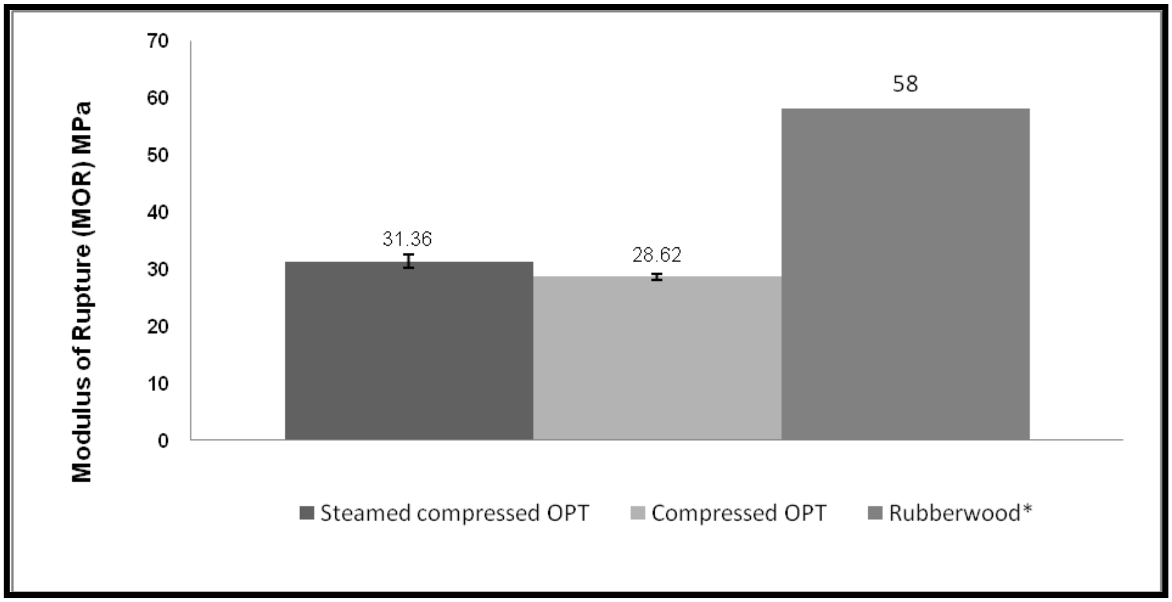


Fig. 3. Modulus of rupture of the samples (*Killmann and Lim 1985)

Both the MOR and MOE showed that steamed compressed OPT had better results compared to the compressed OPT. According to Killman and Lim (1985), the MOR of rubberwood was 58.0 MPa. This indicated that the MOR of steamed compressed OPT was slightly lower in comparison to the solid rubberwood. A study done by Hashim *et al.* (2010) found that the MOR of binderless board from oil palm trunk was 24.95 MPa. The results in Fig. 3 show that the MOR value of the steamed compressed OPT was 31.36 MPa while the compressed OPT was 28.62 MPa. This indicates that when compressing at high temperature, oil palm trunk has the potential to be converted into compressed OPT with improvement in MOR.

In this experiment, the compressed OPT sample is classified as an unmodified wood structure, while the steamed compressed OPT is classified as a modified wood structure. The modified wood structure underwent steam pretreatment, producing partially hydrolyzed hemicelluloses. The cellulose functioned as a component to maintain the mechanical strength of the wood while the lignin provided rigidity and stiffness; therefore, these two components should be kept intact as much as possible. Certain degrees of breakdown of the hemicellulose components, however, should not cause any serious reduction in wood strength but may markedly increase the compressibility of the wood (Hsu *et al.* 1988). According to Horn (1979), steam pretreatment facilitates the flow of hemicelluloses on the fiber surface and softens them in the cell wall to promote fiber flexibility. This increases the bendability in the steamed compressed OPT. According to Rowell and Konkol (1987), certain species of wood will become plastic in bending operations when heat and moisture is applied to the wood.

The modulus of elasticity of the steamed compressed OPT was high, as indicated in Fig. 4. In comparison to the MOE value of rubberwood, steamed compressed OPT had a slightly higher value of MOE, whereas the value was slightly lower for the compressed OPT. Gardner *et al.* (1993) studied the changes in the polymer structure of wood flakes under hot pressing conditions. The results showed an increase in elastic modulus due to an increase in cellulose crystallinity with heat and steam treatment. The increase in crystallinity was attributed to the transition of amorphous polymers from the glassy to the rubbery state.

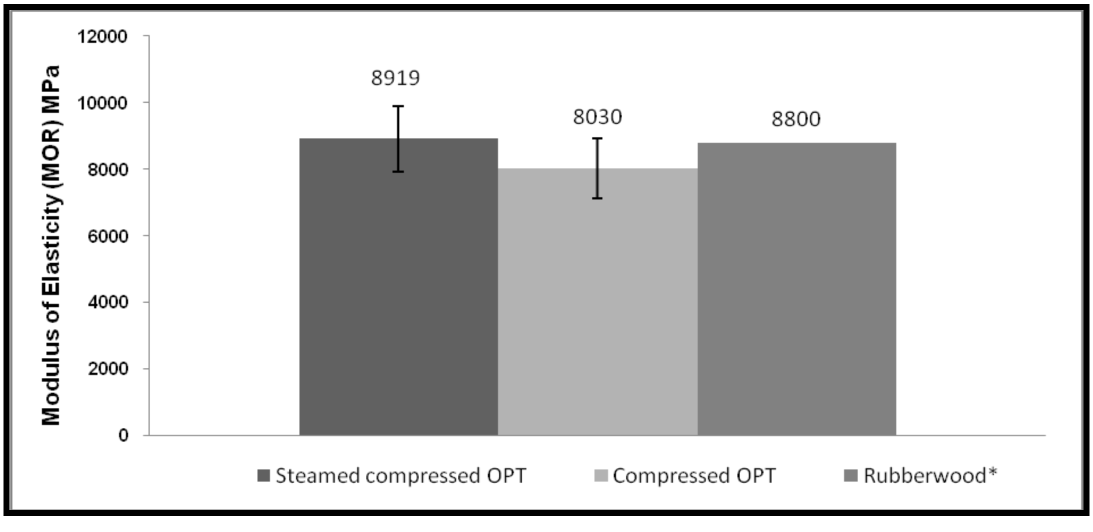


Fig. 4. Modulus of elasticity of the samples (*Killmann and Lim 1985)

When this happened, it increased the mobility of lignin and hemicelluloses subsequently, and allowed reorientation and crystallization of the cellulose microfibrils. This phenomenon can be related to the high MOE result of steamed compressed OPT. Gardner *et al.* (1993) also found that low pressing temperatures results in a decrease in flake strength and stiffness with high pressing temperatures, resulting in an increase in elastic modulus properties. In the steaming pretreatment concept, hemicelluloses will be degraded and removed by hydrolysis, with the lignin and cellulose remaining in the wood. Lignin maintains the rigidity and stiffness, while cellulose provides mechanical strength. By preserving lignin during the steaming process, compressed oil palm trunk can maintain its stiffness and rigidity.

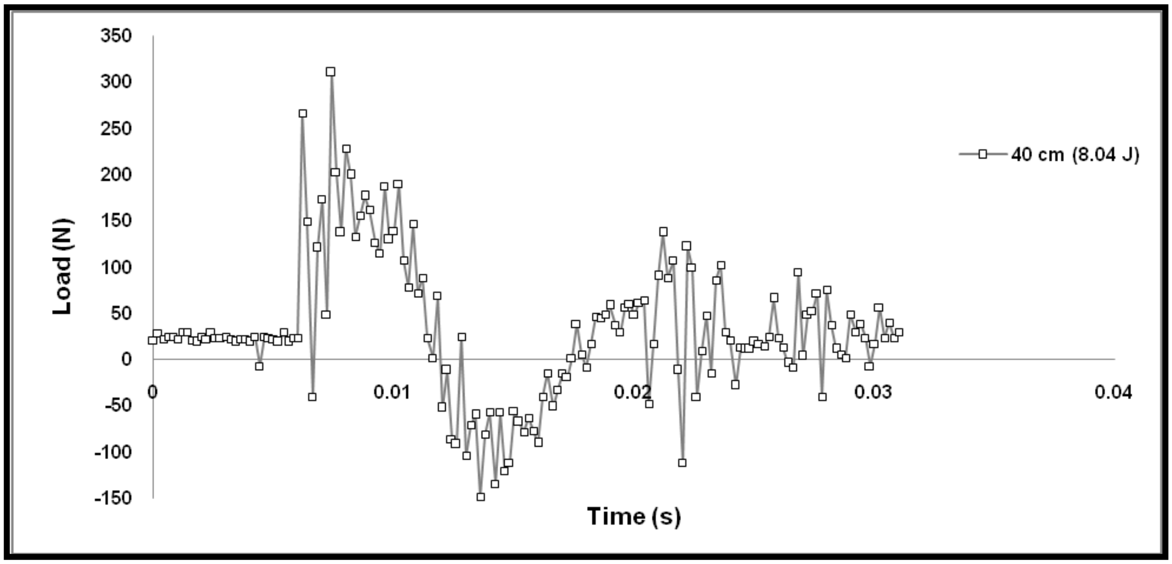
Dynamic Bending

Figure 5 shows the time histories of drop weight impacts onto the steamed compressed OPT and the compressed OPT at 40 cm as a representative for the other height. Figure 6 shows the image of the steamed compressed OPT and the compressed OPT samples after testing was performed. For the steamed compressed OPT, at heights of 10 cm, 20 cm, 30 cm, and 40 cm, the impact energies were 4.39 J, 5.05 J, 7.27 J, and 8.04 J, respectively. For the compressed OPT samples, at heights of 10 cm, 20 cm, 30 cm, and 40 cm the impact energies were 3.73 J, 4.04 J, 6.78 J, and 7.52 J, respectively.

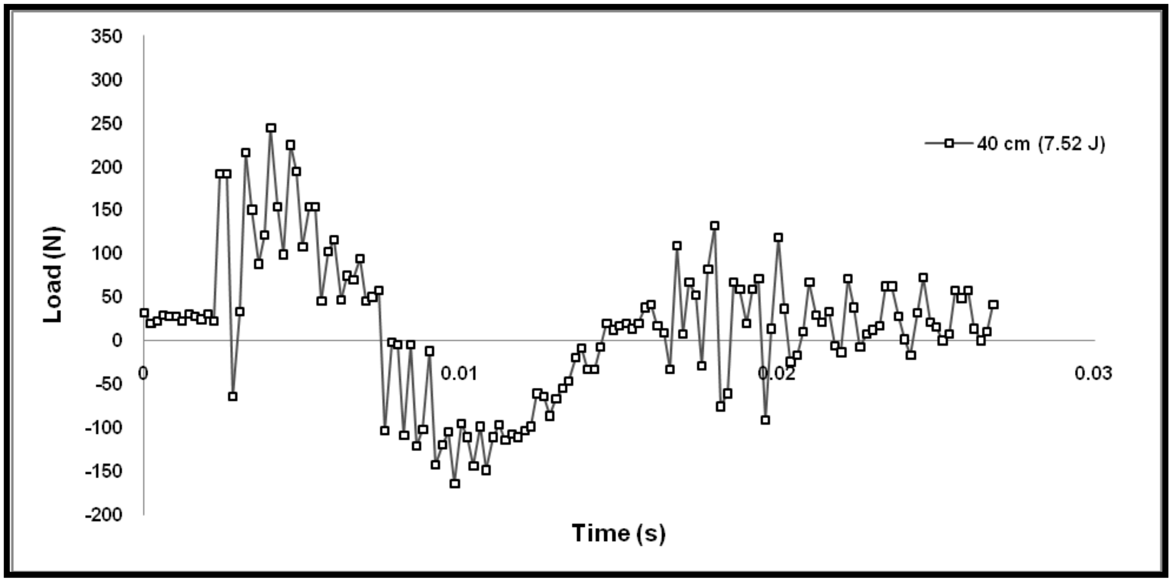
As shown in Figs. 5a and 5b, the steamed compressed OPT had a higher impact strength than the compressed OPT. This is because the modification in chemical composition of the compressed oil palm trunk brings a higher performance in impact strength. This was shown by the high energy absorption needed to resist failure effect or cracks. The compressed OPT sample had little ability to withstand high-rate loading.

A high impact value is due to high energy absorption against energy load. The steamed compressed OPT sample showed the highest value of impact strength. This is because steamed compressed OPT underwent heat treatment that allowed modification of chemical composition; hence, the wood became high in toughness compared to the non-steamed sample. In addition, lignin and cellulose remained in the steamed compressed OPT, but hemicelluloses were eliminated by the steaming process. Moreover, cellulose is a crystalline structure that provides mechanical strength, while lignin provides rigidity and stiffness to steamed compressed OPT (Hsu *et al.* 1988). The steaming process therefore contributes to a high impact value and high toughness. Conversely, the non-steamed sample had a lower impact strength than the steamed sample. This is because the non-steamed sample did not undergo modification of chemical composition, resulting in a reduction in mechanical strength. This caused the lower energy absorption against energy load when testing was performed.

There are three types of interactions between the composite panel and the drop of a hammer. This interaction is dependent on the level of impact energy. First, the drop of the hammer will bounce back when the energy absorbed is very small. Second, there is no rebound when most of the energy is absorbed by the composite through various modes of damage. Finally, under a high level of impact energy, obvious damage can be observed on the composite panel (Sevkat *et al.* 2009). As shown in Fig. 6a the steamed compressed OPT was able to withstand the impact, as the samples were less damaged compared to the control samples shown in Fig. 6b. This means that the steamed compressed OPT samples absorbed more energy compared to the compressed OPT samples. As in Fig. 6b the compressed OPT samples were obviously bent and cracked after testing.



a) Time histories of drop weight impact onto the steamed compressed OPT at 40 cm height



b) Time histories of drop weight impact onto the compressed OPT samples at 40 cm height

Fig. 5. Dynamic bending: a) Time histories of drop weight impact onto the steamed compressed OPT. b) Time histories of drop weight impact onto the compressed OPT samples

Compression Strength

Figure 7 shows a graph of the compression strength results. The steamed compressed OPT had a higher compression strength compared to the compressed OPT samples, with values of 18.54 MPa and 16.9 MPa, respectively. Both samples had low values of compression strength but comparable to the compression strength value of rubberwood, 26.0 MPa (Killman and Lim 1985).

 a) Image of steamed compressed OPT after the dynamic bending test	10 cm (4.39J) 20 cm (5.05J) 30 cm (7.27J) 40 cm (8.04J)
 b) Image of compressed OPT samples after the dynamic bending test	10 cm (3.73J) 20 cm (4.04J) 30 cm (6.78J) 40 cm (7.52J)

Fig. 6. Image of samples after the dynamic bending test: a) Steamed compressed OPT; b) Compressed OPT

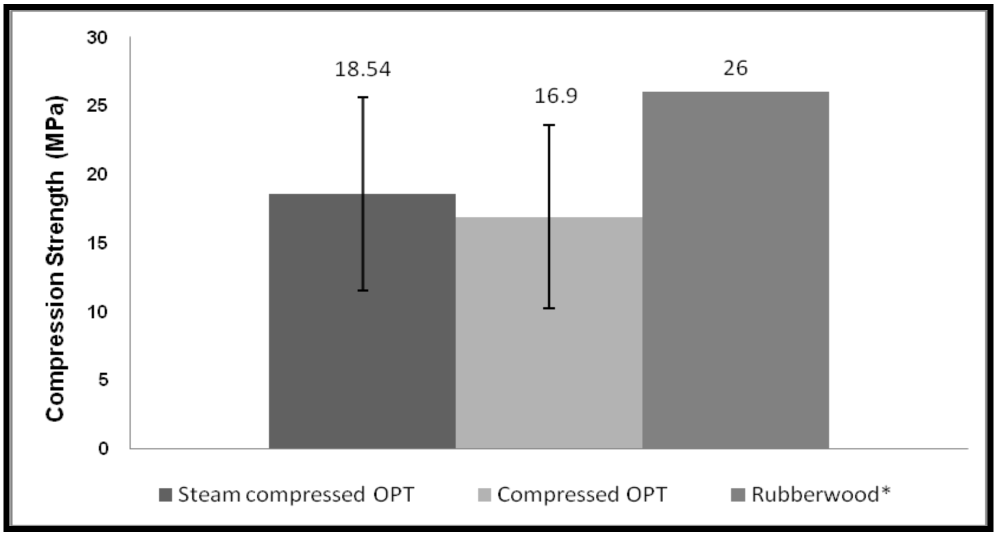
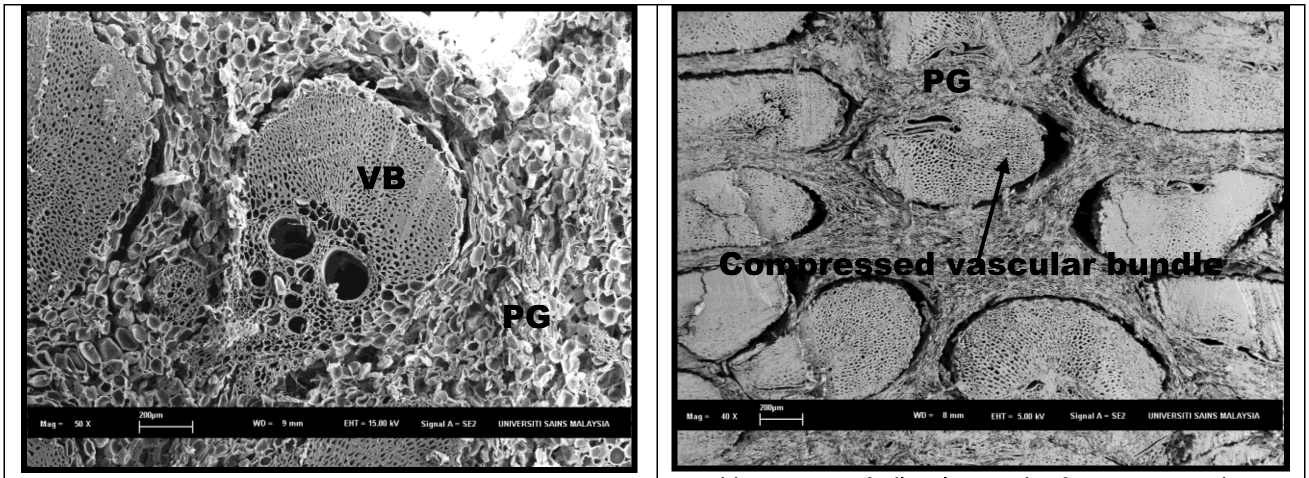


Fig. 7. Compression strength of the samples (Killman and Lim 1985)

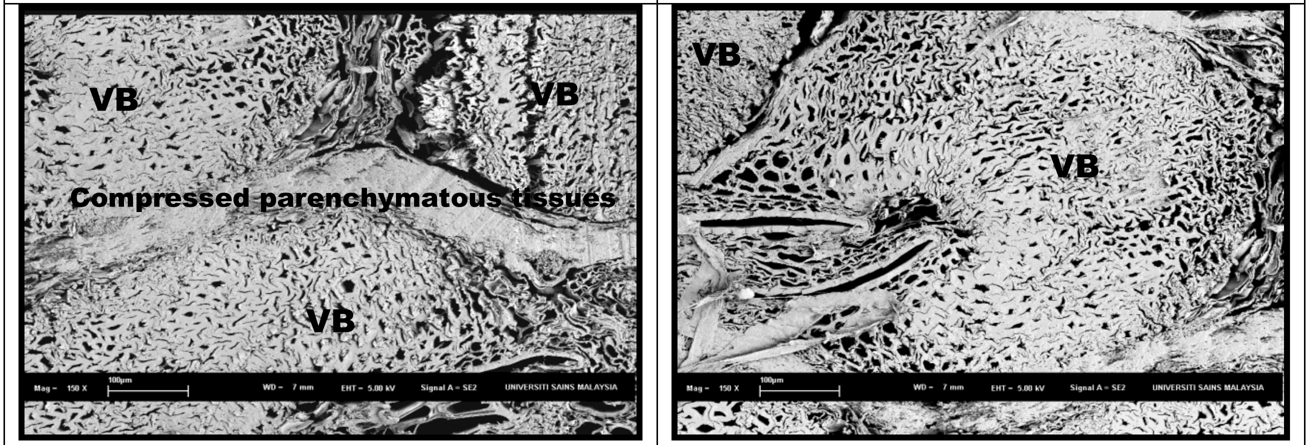
The steaming process modified the lignin structure, and the hemicelluloses started to soften. Under the high temperature, the bound water in the wood started to be released, and polymers started to degrade. This caused degradation of some of the elements that form the wood, which in turn resulted in mass loss. As shown in Fig. 7, the compression strength of the steamed compressed OPT was higher than that of the compressed OPT because of the flexibility of steamed compressed OPT to withstand impact during testing. The steaming process softened the lignin and increased the MOE of the samples, as shown in Fig. 4. This will also affect the properties of compression strength.

Compression strength was also influenced by the density. Referring to Table 1, the density of the steamed compressed OPT was higher than the compressed OPT sample. The high density will provide good mechanical properties in the final product.



a) Image of oil palm trunk before compression

b) Image of oil palm trunk after compression



c) Image of compressed parenchymatous ground tissue surrounded by compressed vascular bundles

d) Image of vascular bundle being compressed

Fig. 8. Micrographs of a cross-section of oil palm trunk using a scanning electron microscope: a) Image of oil palm trunk before compression, b) Image of oil palm trunk after compression, c) Image of compressed parenchymatous ground tissue surrounded by compressed vascular bundles, and d) Image of vascular bundle being compressed.
VB = Vascular bundle, PG = parenchymatous ground tissue

Field Emission Scanning Electron Microscopy (FESEM)

The FESEM micrograph of compressed oil palm trunk is shown in Fig. 8. All pairs of figures reveal the micrograph of the oil palm trunk samples before and after compression. Figure 8a shows the morphology of the oil palm trunk sample before compression, indicating that the sample consists of a vascular bundle and parenchymatous ground tissues. Figure 8b shows the condition of the oil palm trunk after compression. Some void spaces were apparent between the parenchyma and the vascular bundle due to the heating and drying during the manufacturing process. The pressed vascular bundle and parenchymatous ground tissue can be clearly observed in this image. Figure 8c clearly indicates the parenchymatous ground tissue being compressed and surrounded by the vascular bundle. The densities of the compressed OPT increased due to the compression process. This contributes to the good mechanical properties of compressed OPT. In Figs. 8c and 8d, the images are focused on the individual vascular bundle tissues. They clearly show that the vessels and fibers in the vascular bundle are being compressed. The figures obviously show that effect and the changed morphology of the oil palm trunk.

CONCLUSIONS

The results from the research showed that steaming and compressing the oil palm trunk at high temperature improved the properties of the compressed OPT. The steamed compressed OPT showed better physical properties and dimensional stability compared to the compressed OPT. Steaming and compression allowed some modification to occur in the compressed oil palm trunk. Both processes were able to hydrolyze hemicelluloses and soften the lignin in the oil palm trunk. When these two phenomena occurred in the compressed oil palm trunk, the properties of the steamed compressed OPT subsequently improved. From the FESEM micrographs, it can be concluded that the compression process changes the morphology and increases the density of oil palm trunk.

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