

## Quality Improvement of Oil Palm Trunk Properties by Close System Compression Method<sup>1</sup>

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### ABSTRACT

Densification of the inner part of oil palm trunk (OPT) by the close system compression (CSC) method was performed in this study. The effects of the compression temperature and time on the anatomical, physical and mechanical properties of OPT were evaluated. The inner part of OPT with an initial average density of 0.3 g/cm<sup>3</sup> was used as samples. Oven-dried samples were immersed in water and vacuumed until fully saturated and then compressed by CSC at 120, 140, 160 or 180°C for 10, 20, 30 or 40 min. The anatomical characteristics of transverse and radial sections before and after compression were compared by optical microscopy. The physical and mechanical properties, including the density, recovery of set (RS), modulus of elasticity (MOE), modulus of rupture (MOR), and compression parallel to grain were examined. It was observed that the anatomical characteristic of the inner part of OPT (*i.e.*, vascular bundles, vessels, and parenchyma tissue) became flattened, fractured, and collapsed after compression by CSC. The RS decreased with increasing compression temperature and time. The lower RS indicated high dimensional stability. The physical and mechanical properties (*i.e.*, density, MOR, MOE, and compressive strength) of the inner part of OPT increased with increasing compression temperature and time. Compression by the CSC method at 160°C for 40 min was the optimum treatment.

**Keywords :** close system compression, compressed wood, oil palm trunk, physical and mechanical properties, recovery of set

### 1. INTRODUCTION

Indonesia has a very large oil palm tree (*Elaeis guineensis*) plantation, which has reached

more than 8 million ha and spread across 22 provinces (Ministry of Agriculture Republic of Indonesia, 2012). Because of the large area of this plantation, it is creating a significant

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amount of biomass that can be converted into value-added product to provide alternative raw material for the wood industry. When replanted, the oil palm plantation can produce 50.1 m<sup>3</sup>/ha of sawn timber from the hard outer part of the trunk, which is generally only one-third of the entire trunk. In contrast, the soft inner two-thirds of the trunk generally becomes waste owing to several weaknesses such as high moisture content, high shrinkage-swelling, low strength, low durability, and low machining properties (Febrianto and Bakar, 2004). Bakar (2003) reported that the soft inner part of the oil palm trunk (OPT) has a high moisture content of 345%-500%, which causes low dimension stability of the trunk. Therefore, an effort to improve the properties of the inner part of the OPT is urgently needed.

A compression method could be applied to improve the physical and mechanical properties of OPT. Under compression, the density of wood is increased by densification of the pores of the cell structure. Numerous experimental studies of compression of wood from various species have been reported (Kawai *et al.*, 1992; Inoue *et al.*, 1993a; Dwianto *et al.*, 1998a, 1998b; Higashihara *et al.*, 2000; Navi and Heger, 2004; Kamke, 2006; Kutnar and Kamke, 2012; Ratnasingam and Ioras, 2013; Cho *et al.*, 2015). Amin *et al.* (2004) revealed that a compression method significantly increased the physical and mechanical properties of Indonesian tropical woods such as Afrika wood (*Maesopsis eminii*), angšana (*Pterocarpus indicus*), jengkol (*Pithecellobium jiringa*), mango

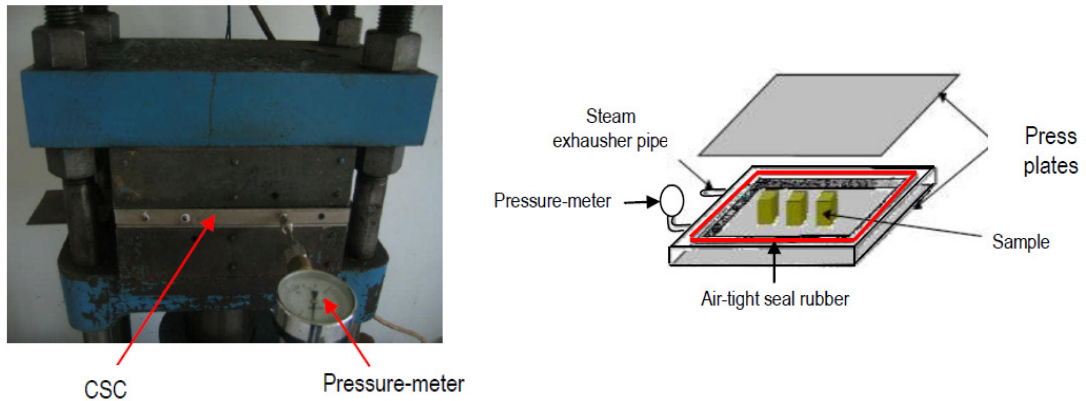
(*Mangifera spp.*), mindi (*Melia azedarach L.*), and randu (*Bombax ceiba L.*).

Recently, compression of non-wood species such as coconut oil wood and OPT have been developed (Wardhani, 2005; Salim *et al.*, 2013; Nordin *et al.*, 2013). However the major problem of compressed wood is recovery of set, which mean after compression, wood will recover to its initial thickness if it is exposed to moisture because of release of its internal stresses. Dwianto *et al.* (1998c) reported that when a compressed wet wood specimen is dried under restraint, the stress gradually decreases until it disappears, and the material is fixed in the deformed state. Dwianto *et al.* (1998c, 1998d, 1999) have studied the mechanism of permanent fixation of compressive deformation in wood. Inoue *et al.* (1993b) developed a compression method to improve permanent fixation of compressive deformation in a short time by hygrothermal treatment using moisture in wood, which is called the close system compression (CSC) method. This method resulted in a good fixation of randu (*Bombax ceiba*) wood (Amin and Dwianto, 2006). Therefore, the objective of this research was to analyze the physical, mechanical, and anatomical properties of OPT compressed by the CSC method.

## 2. MATERIALS and METHODS

### 2.1. Materials

OPT approximately 40 years in age with a diameter of 40 cm was obtained from Bogor,



**Fig. 1.** Hot-press machine (left) equipped with CSC equipment (right).

Indonesia. Samples were prepared from the inner part of the OPT and cut into pieces 150 mm × 50 mm × 20 mm in length, width, and thickness, respectively. The samples were dried at 60°C until they reached a constant weight, and then the weight and dimensions were measured to determine their initial density. The average density of the samples after drying was 0.3 g/cm<sup>3</sup>.

## 2.2. Methods

### 2.2.1. Compression process

The OPT samples were compressed by a hot press machine equipped with CSC parts, as shown in Fig. 1. The CSC equipment consisted of a rectangular stainless steel frame, upper and lower press plates, a high-temperature-resistant airtight silicone rubber seal, a pressure meter, and a steam exhaust pipe. The CSC frame and hot press plates had the same size, 250 mm × 250 mm. The CSC frame was equipped with silicone rubber on its upper and lower parts to

seal it perfectly when pressing was applied. One side of the frame had two holes for pressure measurement and a steam exhaust pipe to release the vapor when the compression process finished.

The CSC frame was placed in the lower part of the pressing plate so that the frame was located between the upper and lower parts of the pressing plates. After OPT samples were placed inside the frame, a cylindrical hydraulic piston pushed up the lower part of the pressing plate, and the compression process began. Samples were compressed to a compression ratio of 50% at 120, 140, 160, or 180°C for 10, 20, 30, or 40 min, with four replications under each condition. The final size of the samples after compression was 150 mm × 50 mm × 10 mm in length, width, and thickness, respectively. The samples were conditioned under a relative humidity of 70 ± 5% at 25 ± 2°C for 2 weeks before further testing.

### 2.2.2. Anatomical observation

The anatomical structure observed in transverse and radial sections of OPT was analyzed. Slices 30  $\mu\text{m}$  in thickness were obtained using a sliding microtome. The sections were stained with Safranin-Astra blue, dehydrated in a graded series of alcohol solutions (50%, 70%, 90%, 95%, and 99%), mounted in Canada balsam, and observed with an optical microscope (Nikon Eclipse E600, Japan).

### 2.2.3. Physical properties

The air-dry density of samples with dimensions of 40 mm  $\times$  20 mm  $\times$  20 mm was determined in accordance with British Standard 373 (1957) by measuring their air-dry weight ( $m$ ) and volume ( $v$ ). The air-dry density was calculated as follows:

$$D \text{ (g/cm}^3\text{)} = \frac{m}{v}$$

The fixation value was obtained from a recovery test of samples with dimensions of 30 mm  $\times$  20 mm  $\times$  10 mm. The recovery test was performed by soaking the samples in room-temperature water for 24 h and then in hot water (100°C) for 30 min (Dwianto *et al.*, 1997). The recovery of set (RS) was calculated as follows:

$$RS \text{ (\%)} = \frac{T_r - T_c}{T_o - T_c} \times 100\%$$

where  $T_o$  is the initial thickness,  $T_c$  is the thickness after compression, and  $T_r$  is the thickness after recovery. All the dimensions of the sam-

ples were measured in the oven-dry condition.

### 2.2.4. Mechanical properties

Modulus of rupture (MOR), modulus of elasticity (MOE), and compressive strength tests were conducted in accordance with British Standard 373 (1957) using a universal testing machine (Model 4482, Instron, Norwood, MA, USA). The sample dimensions for the MOR and MOE tests were 150 mm  $\times$  10 mm  $\times$  10 mm. Three-point bending was applied over an effective span of 100 mm at a loading speed of 5 mm/min. The dimensions of the samples for the compressive strength test were 40 mm  $\times$  10 mm  $\times$  10 mm. The MOR, MOE, and compressive strength ( $R$ ) were calculated as follows:

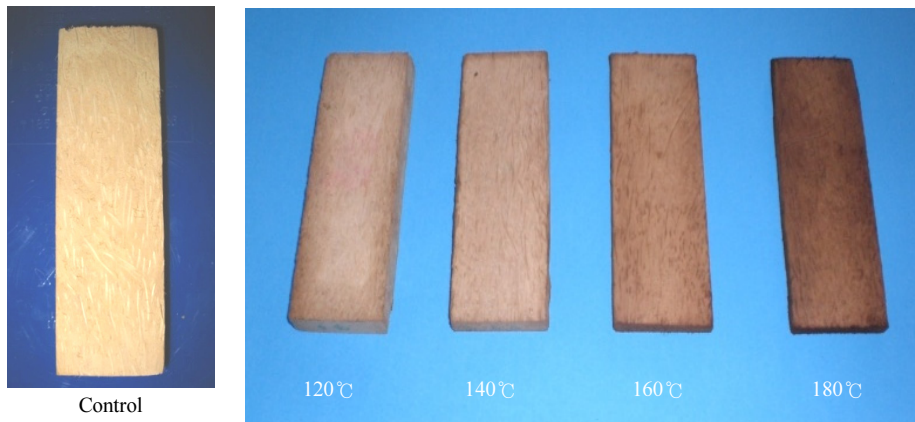
$$MOR \text{ (N/mm}^2\text{)} = \frac{P_p L^3}{4Y_p b t^3}$$

$$MOE \text{ (N/mm}^2\text{)} = \frac{3PL}{2bt^2}$$

$$R \text{ (N/mm}^2\text{)} = \frac{P}{bt}$$

where  $P$  is the maximum load (N),  $P_p$  is the load at the proportional limit (N),  $Y_p$  is the deflection (mm),  $L$  is the span length (mm),  $w$  is the sample width (mm), and  $t$  is the sample thickness (mm).

To determine the effect of the compression temperature and time on the properties of OPT, the data were compared with those of a control. All runs were performed with four replications.



**Fig. 2.** Visual appearance of OPT before and after compression by CSC method.

### 3. RESULTS and DISCUSSION

#### 3.1. Visual appearance

Compression of OPT by the CSC method at temperatures of 120-180°C caused darkening of the wood surface color. Fig. 2 shows that the surface of OPT became darker with increasing heating temperature. OPT compressed at 180°C showed the darkest color among the samples. Hayashi *et al.* (2002) stated that wood heat treatment at 180°C degraded the lignin, which darkened the wood color. Shi *et al.* (2011) reported that heat treatment had a darkening effect on wood tissue, and the color became darker with increasing temperature. The color change is attributed to oxidation of phenolic compounds, the presence of reduced sugars and amino acids, emanation of formaldehydes, formation of quinines, or caramelization of holocellulose components during heat treatment (Sundqvist, 2002; Sandoval-Torres *et al.*, 2010; Hidayat *et al.*, 2015).

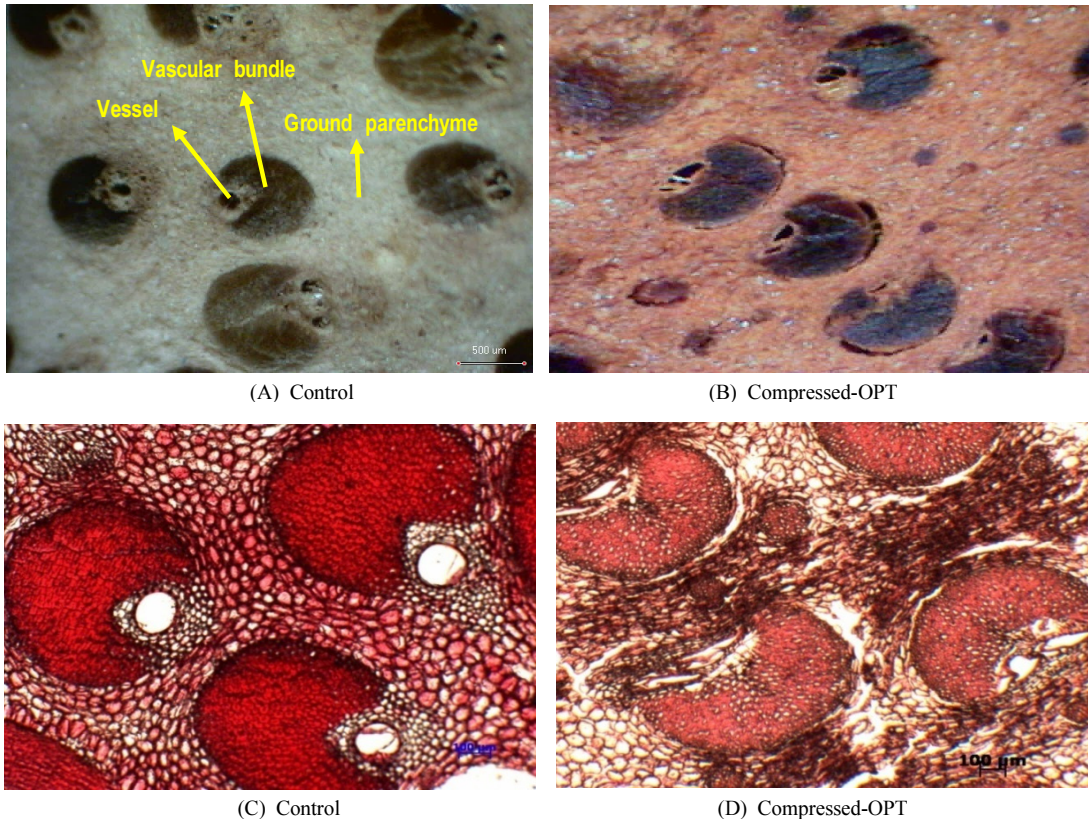
#### 3.2. Anatomical properties

Fig. 3 and 4 show the anatomical characteristics of OPT before and after compression by the CSC method. The vascular bundles, vessels, and ground parenchyma tissue of OPT before compression were round and intact, whereas after compression they showed flattened shapes. Moreover, vessels and parenchyma cells were severely fractured and collapsed after compression.

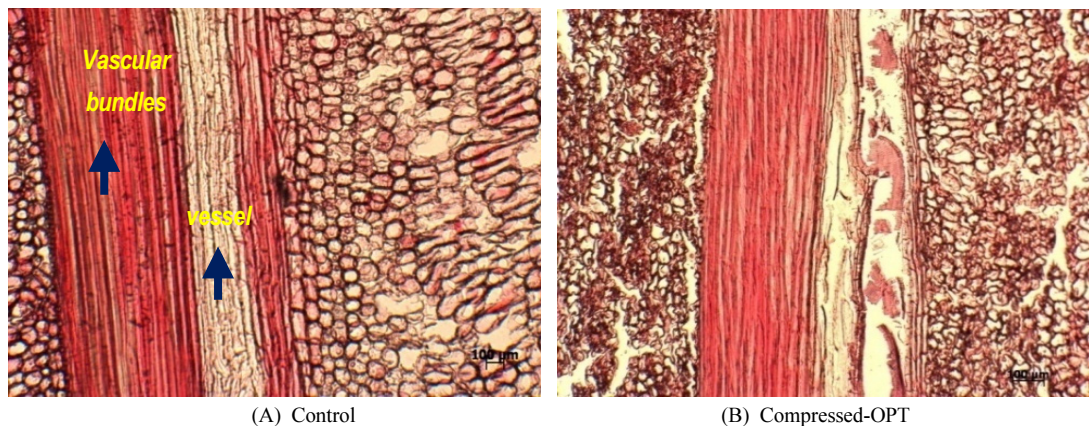
#### 3.3. Physical properties

The average density and RS of OPT after compression by the CSC method are shown in Fig. 5. The compression temperature and time used in the CSC method contributed to the changes in the density and RS. Overall, the results showed that compression by the CSC method increased the density of OPT, which increased its dimensional stability. The density after compression by the CSC method increased

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**Fig. 3.** Optical micrographs of OPT in cross section: (A) control, (B) compressed OPT at 30× magnification, (C) control, (D) compressed OPT at 50× magnification.



**Fig. 4.** Optimal micrographs of OPT in radial section: (A) control and (B) compressed OPT at 50× magnification.

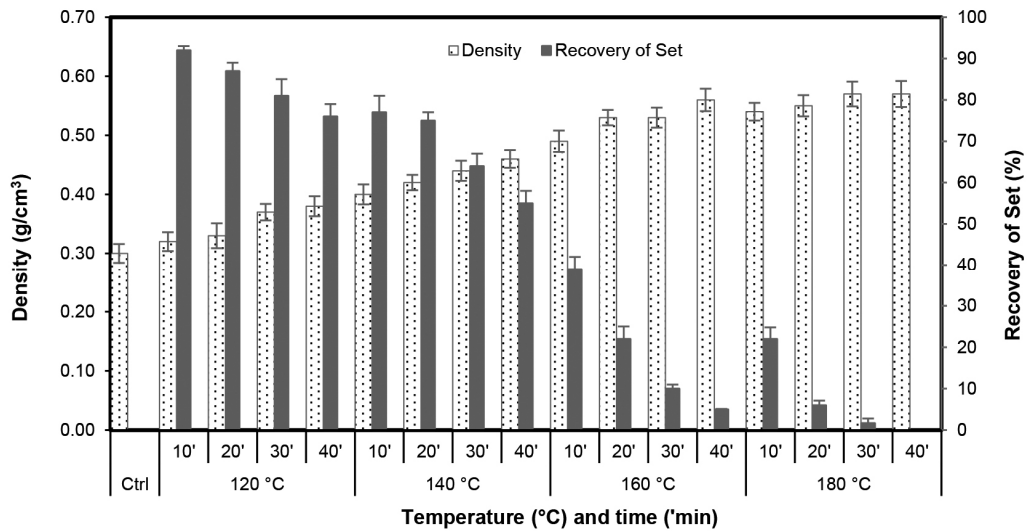


Fig. 5. Recovery of set (RS) and density after compression by CSC method.

with decreasing RS. The decrease in the RS contributed to the reduction of the OPT thickness and consequently reduced the overall volume of the sample, whereas its mass was relatively stable. The results showed that the density of OPT after compression by the CSC method increased from  $0.30 \text{ g/cm}^3$  to  $0.31\text{-}0.57 \text{ g/cm}^3$ , or by 3.33%-90%. The highest density was achieved after compression at  $180^\circ\text{C}$  for 40 min.

The results were consistent with those of previous studies reported by Sulistyono (2001) and Kutnar and Kamke (2012). Compression of *Agathis loranthifolia* at a compression ratio of 50% increased the density from  $0.43\text{-}0.46 \text{ g/cm}^3$  to  $0.70\text{-}0.85 \text{ g/cm}^3$  in the radial direction and to  $0.69\text{-}0.84 \text{ g/cm}^3$  in the tangential direction (Sulistyono, 2001). Kutnar and Kamke (2012) reported that the density of hybrid poplar (*Populus deltoides* × *Populus trichocarpa*) in-

creased linearly with increasing temperature after compression under a load of 5.5 MPa, reaching a density increase of 98%-208%.

The RS decreased with increasing compression temperature and time. A lower RS indicates higher dimensional stability of compressed OPT. The RS after compression at  $120^\circ\text{C}$  for 10 min was 92%; it decreased to 1.74% after compression at  $180^\circ\text{C}$  for 30 min. The RS after compression at 120 and  $140^\circ\text{C}$  decreased gradually with increasing compression time. However, the RS after compression at  $160^\circ\text{C}$  showed a dramatic decrease with increasing time. The lowest RS, which indicated reduction of the thickness of compressed OPT, was -3.75%. The value was achieved after compression at  $180^\circ\text{C}$  for 40 min.

The results show that almost complete fixation of set (an RS value of close to 0%) was achieved after compression at  $180^\circ\text{C}$  for 30

**Table 1.** MOR, MOE, and compression strength of OPT after compression by CSC method

Temperature	Time (min)	MOE (N/mm <sup>2</sup> )	MOR (N/mm <sup>2</sup> )	Compressive strength (N/mm <sup>2</sup> )
Control	-	924.37 (132.39)	7.80 (0.74)	5.37 (0.60)
120°C	10	1,323.90 (172.70)	8.91 (1.16)	6.39 (0.67)
	20	1,408.33 (176.13)	9.30 (0.74)	6.35 (0.46)
	30	1,656.05 (218.88)	9.60 (0.92)	7.64 (0.73)
	40	1,711.46 (227.32)	10.09 (1.39)	7.67 (0.67)
140°C	10	1,814.62 (289.20)	9.98 (1.17)	8.89 (1.40)
	20	2,056.16 (350.88)	10.55 (0.99)	10.24 (1.25)
	30	1,974.18 (293.91)	12.76 (1.42)	10.38 (1.44)
	40	2,281.81 (304.99)	13.94 (1.40)	10.81 (1.61)
160°C	10	2,169.92 (189.27)	14.30 (2.69)	10.28 (1.43)
	20	2,273.77 (315.97)	18.97 (1.43)	11.41 (1.54)
	30	2,463.53 (289.39)	19.65 (2.22)	11.72 (1.29)
	40	2,706.05 (273.80)	19.94 (2.30)	11.99 (1.39)
180°C	10	2,245.13 (241.34)	17.28 (1.15)	10.21 (1.46)
	20	2,312.70 (358.63)	19.54 (3.01)	10.47 (0.38)
	30	2,480.89 (366.08)	19.67 (0.72)	10.50 (1.10)
	40	2,326.04 (169.95)	18.27 (2.57)	10.67 (1.43)

Note: Numbers in parentheses are standard deviations.

min, with an RS value of 1.74%. Compression by the CSC method achieved faster fixation than a heat treatment method reported in previous studies (Inoue and Norimoto, 1991; Norimoto *et al.*, 1993). Compression of sugi (*Cryptomeria japonica* D. Don) achieved fixation after heat treatment at 180°C for 20 h, 200°C for 5 h, and 220°C for 3 h (Inoue and Norimoto, 1991). Norimoto *et al.* (1993) studied bending deformation in mizunara (*Quercus mongolica*) and revealed that almost complete fixation of set was achieved by heat treatment above 30 h at 160°C and 12 h at 180°C. Inoue *et al.* (2008) stated that three mechanisms are essential to obtain permanent fixation: 1) prevention of re-softening of wood by conversion

of its components to less water-accessible components, as the set does not recover unless re-softening of the matrix occurs, 2) formation of covalent cross-links between the wood components in the deformed state, and 3) release of the elastic stresses and strains stored in the microfibrils and matrix.

### 3.4. Mechanical properties

The MOE, MOR, and compression parallel to grain of OPT after compression by the CSC method are shown in Table 1. The compression temperature significantly affected MOE, MOR, and compression parallel to grain. Statistical analyses revealed that the compression time sig-

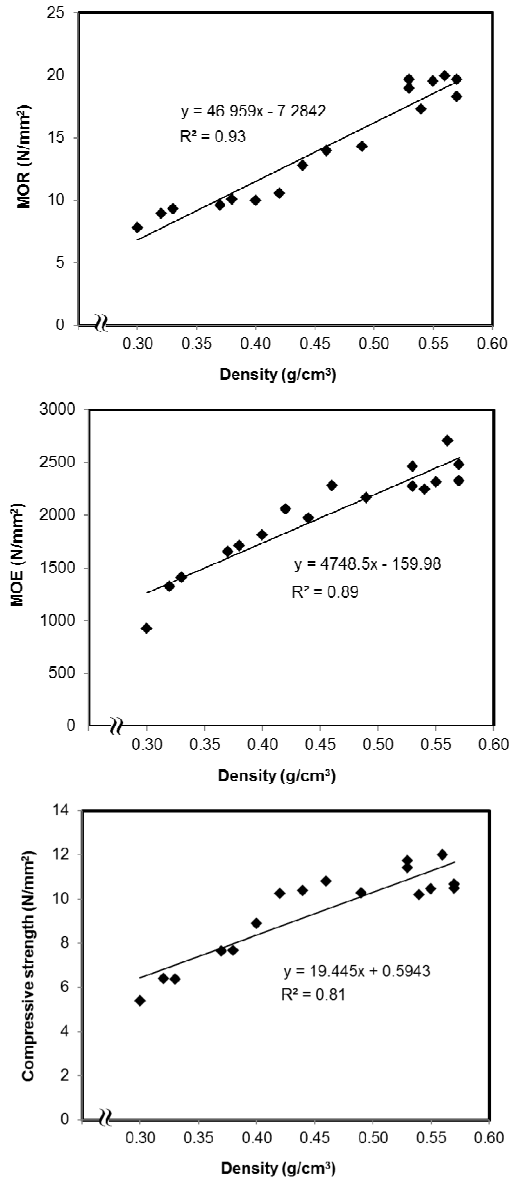


nificantly affected MOE and MOR, while its effect on compression parallel to grain was not yet significant. On the whole, the mechanical properties increased with increasing compression temperature and time.

The initial MOE of OPT before compression was 924.37 N/mm<sup>2</sup>. It increased to 1,323.90-2,706.05 N/mm<sup>2</sup>, or by 43.22%-192.74%. The MOR of OPT also increased from 7.80 N/mm<sup>2</sup> to 8.91-19.94 N/mm<sup>2</sup>, or by 14.31%-155.81%. A similar trend also appeared in the compressive strength, which increased from 5.37 N/mm<sup>2</sup> to 6.39-11.99 N/mm<sup>2</sup>, or by 18.93%-123.20%, after compression. The highest mechanical properties were achieved after compression at 160°C for 40 min.

Sulistyono (2001) reported that compression of *Agathis lorantifolia* with a compression ratio of 50% increased the MOE, MOR, and compression parallel to grain by 45.08%-152.20%, 26.98%-103.84%, and 47.94%-86.21%, respectively. Amin *et al.* (2004) reported that compression of Afrika, angšana, jengkol, mango, mindi, and randu wood using a compression ratio of 33% increased the MOE by 41.18%-127.55% and the MOR by 41.25%-81.37%. The results indicate that the compression method significantly improved the mechanical properties of wood.

The density is one of the main factors affecting the properties of wood and other lignocellulosic materials. A compression ratio of 50% changed the thickness of OPT, thus increasing its density, and affected many properties, including the mechanical properties. The results showed the relationship between the



**Fig. 6.** Relationship between density and mechanical properties of OPT.

density and mechanical properties of OPT, as shown in Fig. 6.

The density increased the MOR, MOE, and compressive strength, which resulted in a strong

relationship, as shown by high values of the coefficient of correlation ( $R^2$ ) of 0.89, 0.94, and 0.81 for the MOE, MOR, and compressive strength, respectively. Similarly, Kutnar and Kamke (2012) reported that the density, MOE, and MOR of hybrid poplar after compression by heat treatment increased linearly with increasing temperature.

#### 4. CONCLUSION

The inner part of OPT was densified by the CSC method. Compression at high compression temperatures and times resulted in darker OPT color. The anatomical morphology of OPT, such as the vascular bundles, vessels, and parenchyma tissue, became flattened, fractured, and collapsed after compression CSC. The RS of OPT decreased with increasing compression temperature and time. The lower RS indicated high dimensional stability. Compression of OPT by the CSC method successfully increased its density, MOE, MOR, and compressive strength. The highest mechanical properties were achieved after compression at 160°C for 40 min.

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