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EFFECTS OF SUPERHEATED STEAM TREATMENT ON THE PHYSICAL AND MECHANICAL PROPERTIES OF LIGHT RED MERANTI AND KEDONDONG WOOD

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In this study, the effects of superheated steam treatment on physical and mechanical properties of light red meranti (*Shorea* spp.) and kedondong (*Canarium* spp.) wood were investigated. Wood samples with dimensions of 25 mm thickness × 25 mm width × 410 mm length were heat treated using superheated steam. Wood samples were heat treated at nine treatment levels ranging from 172 to 228 °C and 95 to 265 min. A set of untreated wood served as control. The physical properties such as mass loss, equilibrium moisture content (EMC) and moisture excluding efficiency (MEE) were determined. Bending strength, modulus of rupture and modulus of elasticity of the treated and untreated wood samples were determined. Mass loss was observed in the treated samples and its extent increased with increasing temperature and time. EMC of the treated samples was reduced and high MEE values were recorded, indicating decreased hygroscopicity of the treated wood. On the contrary, bending strength of the treated wood was negatively affected by the superheated steam treatment. Such reductions in mechanical properties became greater with increasing temperature and exposure time.

Keywords: *Shorea* spp., *Canarium* spp., heat treatment, mass loss, equilibrium moisture content, moisture excluding efficiency, bending strength

INTRODUCTION

Wood has been used as raw material for many applications due to its excellent properties such as good strength-to-weight ratio and aesthetic appearance. However, wood is susceptible to biodeterioration and dimensional instability because of its hygroscopic nature. The common practice to protect wood from wood-decaying organism is by applying chromated copper arsenate (CCA). Unfortunately, CCA is toxic and may leach out during its service life and impose serious threats to the environment and human (Lebow et al. 2008). Wood preservation methods without using harmful chemicals are prevalent in recent years. Increasing environmental awareness prompts the development of heat treatment in enhancing the properties of wood, especially dimensional stability and durability. Heat treatment, or thermal treatment, is an environmentally friendly approach where wood properties can be improved by the rearrangement of hemicelluloses, lignin and cellulose during the treatment without application of toxic chemicals (Guo et al. 2017). Heat treatment of wood is gaining popularity worldwide and is currently the most investigated treatment approach for wood owing to the stringent regulations in the application of toxic wood preservatives (Salman et al. 2016).

Heat treatment of wood is an effective method to reduce the equilibrium moisture content (EMC) and improve dimensional stability of wood (Wang & Cooper 2005, Kortelainen et al. 2006). The main drawback of the treatment is that it is detrimental to mechanical properties especially the static and dynamic bending strength (Esteves et al. 2007a, b). Heat treatment can be conducted in various heating media to improve the physical and durability properties of wood. For example, Umar et al. (2016) treated rubberwood in hot palm oil and reported that the decay resistance of the treated wood was significantly improved. Apart from oil, water also is one of the promising heating media in hydrothermal treatment (Endo et al. 2016, Saliman et al. 2017). The resulted improvement in physical properties is highly dependent on treatment temperature and time (Sundqvist et al. 2006). Wood has been treated under superheated steam and inert atmosphere to avoid combustion (Esteves et al. 2007b).

Light red meranti (*Shorea* spp.) and kedondong (*Canarium* spp.) are two tropical forest species that exist abundantly in Malaysia. *Shorea* is the most common species in the hill dipterocarp forests of Peninsular Malaysia and is an important source of timber as the supply from lowland forests continue to shrink over the years (Yagihashi et al. 2016). Kedondong wood is one of the most consumed light hardwood species by sawmills and plywood/veneer mills in Peninsular Malaysia. Both wood species are light- density hardwood and reported as non-durable against fungal and insect attack. In addition, they are dimensionally instable and difficult to treat with preservatives (MTIB 2010). Therefore, heat treatment is proposed to improve some of these properties. Unfortunately, most of the studies on heat treatment were focused on the temperate wood species. Thermal treatment improves the dimensional stability of other lignocellulosic materials such as *Eucalyptus tereticornis* and oil palm trunks (Choowang & Hiziroglu 2015, Poonia & Tripathi 2016). Unfortunately, the studies of the effects of heat treatment on properties of tropical hardwood such as light red meranti and kedondong woods are limited. Temperate hardwood differs from tropical hardwood in terms of chemical composition and anatomical structure. Thus, the aims of this study were to determine the effects of superheated steam on the physical and mechanical properties of light red meranti and kedondong wood.

MATERIALS AND METHODS

Preparation of raw material

Light red meranti and kedondong wood were obtained from a local sawmill. Pre-conditioned samples (EMC 12%) with dimensions of 25 mm thickness × 25 mm width × 410 mm length were prepared for the treatment. The prepared samples were randomly divided into 10 groups (one group for untreated wood and nine groups for heat-treated wood) with three replicates for each group. The treatment conditions for each group were decided based on the procedures stated in the following section.

Optimising heat treatment condition

Heat treatment normally takes place at temperatures ranging from 160–260 °C with most studies using temperature below 220 °C. Based on the study conducted by Umar et al. (2016), temperature and time ranging from 172 to 228 °C and 95 to 265 min respectively were used as benchmark values for the treatment parameters in this study. Central composite design using response surface methodology was conducted to investigate the effects of these two independent variables (treatment temperature and time) on the wood properties (Table 1). Wood samples were treated in a superheated steam oven at the designated temperature and time. The schematic view of the superheated steam oven treatment is shown in Figure 1. A set of untreated wood samples served as control for comparison purposes.

Evaluation of physical properties

After heat treatment, the samples (25 mm thickness × 25 mm width × 410 mm length) were

Table 1 Experimental conditions of heat treatment using superheated steam

Treatment	Temperature (°C)	Time (min)
T1	172	180
T2a	180	120
T2b	180	240
T3a	200	95
T3b	200	180
T3c	200	265
T4a	220	120
T4b	220	240
T5	228	180

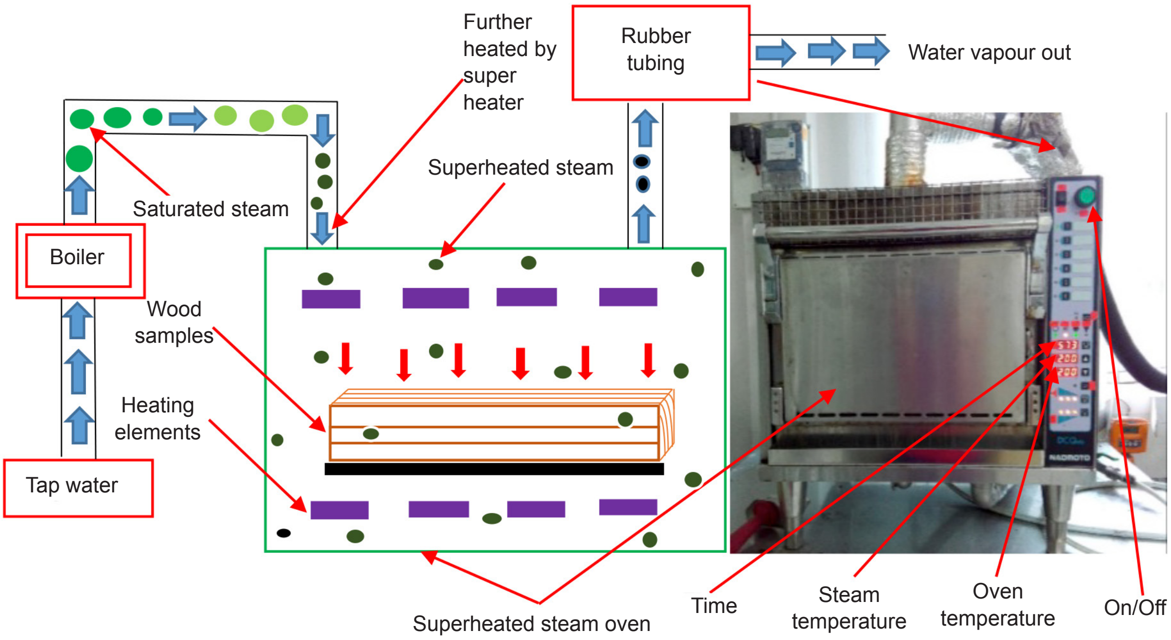

Figure 1 Schematic view of superheated steam treatment

cooled in a conditioning room at 20 ± 2 °C and relative humidity of 65 ± 5% for 3 weeks. When constant weights were reached, mass and density loss of the samples caused by heat treatment were calculated. Block samples with 25 mm thickness × 25 mm width × 25 mm length were then prepared for the determination of EMC and moisture excluding efficiency (MEE) of the samples. The samples were dried at 103 ± 2 °C to constant weights. After determining the oven-dry weight and volume, the block samples were kept in a desiccator with relative humidity of 98 ± 2% measured by using hygrometer. The samples were placed on top of mesh wire where a petri dish filled with water was placed at the bottom of the desiccator at ambient temperature until the test blocks reached constant weights. The conditioned blocks were again weighed and the EMC and MEE of the samples were calculated as follows:

$$\text{EMC (\%)} = 100\ (W_2 - W_1)/W_1 \qquad (1)$$

where W_1 = oven-dry weight (g) and W_2 = constant weight after reconditioning (g).

$$\text{MEE (\%)} = 100\ (E_u - E_t)/E_u \qquad (2)$$

where E_u = EMC of untreated samples (%) and E_t = EMC of treated samples. EMC and MEE of the samples were calculated in triplicate for treated and untreated samples.

Mechanical properties

The static bending tests, modulus of rupture (MOR) and modulus of elasticity (MOE) of the treated wood were determined following the standard test procedures specified in ASTM D143-09 (ASTM 2009) to determine the effect of treatment parameters on mechanical strength of wood. The testing was done on the samples with dimensions of 25 mm thickness × 25 mm width × 410 mm length using a universal testing machine with load capacity of 30 kN. MOR and MOE were determined from the measured load deformation curves using the equations given below:

$$\text{MOR (MPa)} = 3P_mL^3/2bh^2 \qquad (3)$$

$$\text{MOE (MPa)} = P_tL^3/4Dbh^3 \qquad (4)$$

where P_m = maximum breaking load (MPa), P_t = load at below proportional limit (MPa), L = span of test specimen (mm), D = deflection of midspan resulting from load at below proportional limit (mm), b = width and h = height of the test sample (mm).

Statistical analysis

Data were analysed using analysis of variance (ANOVA) to assess the effects of treatment on the physical and mechanical properties of treated wood. The differences between mean values of each treatment level were further separated using Duncan's multiple range test at $p \leq 0.05$.

RESULTS AND DISCUSSION

Mass loss

Mass loss of light red meranti and kedondong wood after treatment are presented in Figure 2. The mass loss was significantly affected by heat treatment for both species. and it increased as temperature rose except for T2a, T3a and T3b for light red meranti and T3a for kedondong. Significant loss of mass was observed when temperature reached 220–228 °C (T4a, T4b and T5) but it was maximum (i.e. 11.48 and 18.55% for light red meranti and kedondong respectively) at 228 °C for 180 min (T5). This concurs with result from Kortelainen et al. (2006), who reported that the higher the treatment temperature and the longer the time, the more significant are the changes of mass in the wood. It is interesting to note that the mass loss of kedondong was higher compared with light red meranti. The higher degradation rate of holocellulose in kedondong wood is one of the major factors that contributes to the higher mass loss of the species compared with light red meranti.

Equilibrium moisture content

EMCs for both species after treatment are presented in Figure 3. EMC of the treated samples decreased compared with that of untreated samples and the rate of decrement was greater with extended treatment temperature and time. The lowest EMC for kedondong (4.77%) was recorded when subjected to treatment temperature of 220 °C for 240 min (T4b), a reduction of 59% in comparison with control (11.66%). On the other hand, EMC of light red meranti reduced from 12.81 to 4.65% when the wood was treated at 228 °C for 180 min (T5). From Figure 3, it can be seen that temperature is more influential in reducing EMC for both species compared with treatment time. For example, light red meranti and kedondong wood treated at 180 °C for 240 min (T2b) had EMC of 7.56 and 7.80% respectively. When higher temperature but shorter time was applied (200 °C for 180 min), EMC of both species reduced to 6.97 and 6.57% respectively. Thus, treatment time can be shortened by more than 60 min by raising the temperature by 20 °C. Similar effects were observed in a study by Paul et al. (2006). The reduction in EMC can be explained by lesser amount of water being absorbed by the cell walls after heat treatment due to decreased hydroxyl

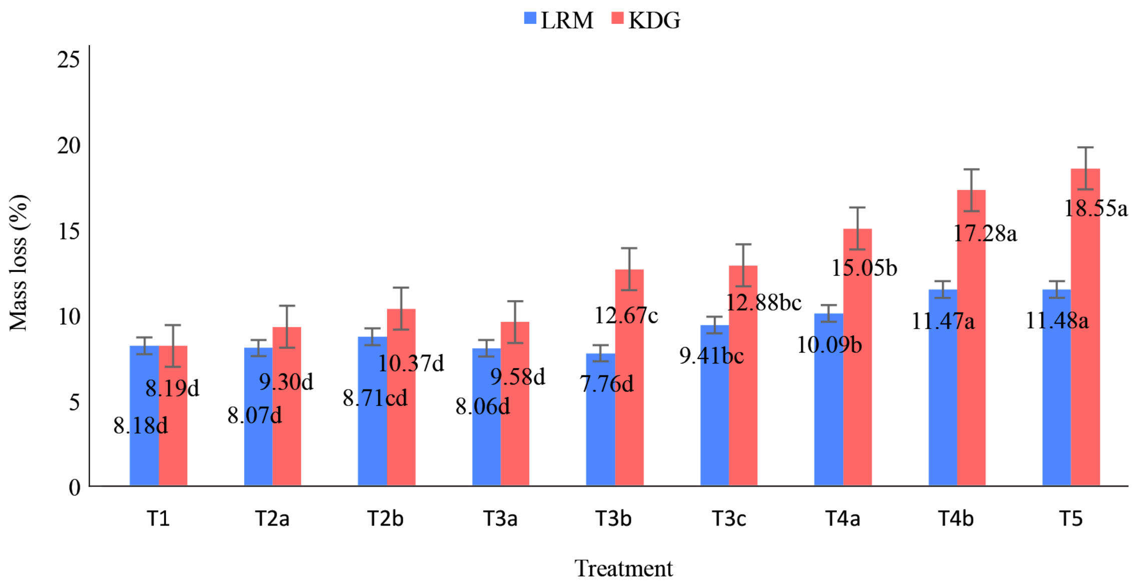

Figure 2 Mean mass loss of light red meranti (LRM) and kedondong (KDG) wood treated at different temperatures and times; T1 =172 °C, 180 min, T2a = 180 °C, 120 min, T2b = 180 °C, 240 min, T3a = 200 °C, 95 min, T3b = 200 °C, 180 min, T3c = 200 °C, 265 min, T4a = 220 °C, 120 min, T4b = 220 °C, 240 min, T5 = 228 °C, 180 min; within the same species, means followed by the same letters are not significantly different at $p \leq 0.05$

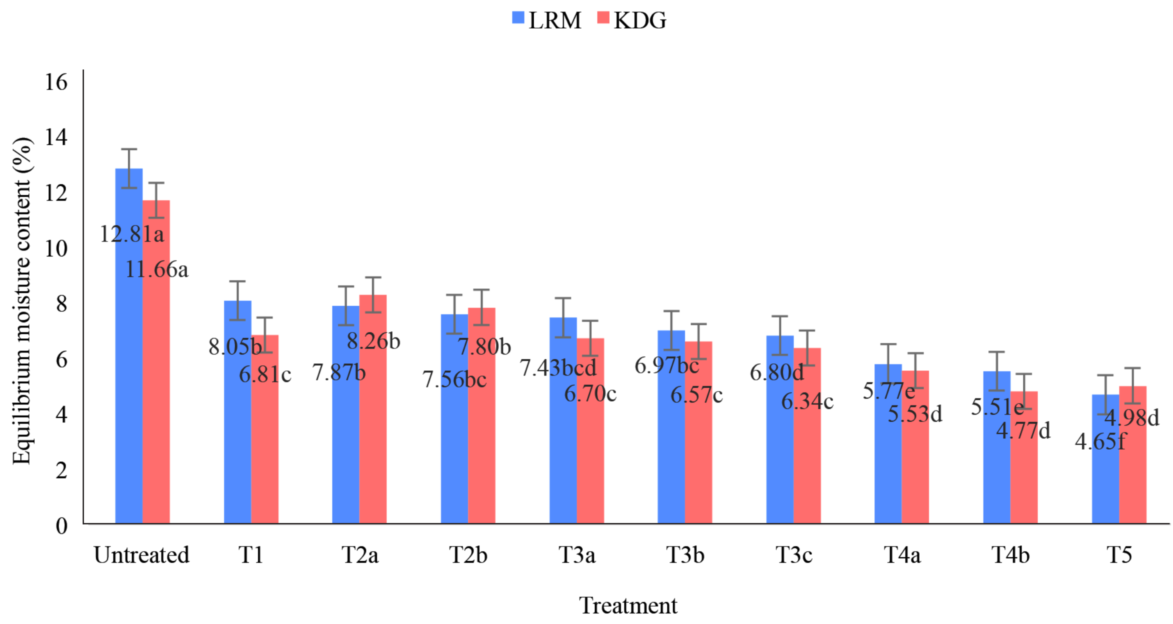

Figure 3 Equilibrium moisture content of light red meranti (LRM) and kedondong (KDG) wood treated at different temperatures and times; T1 =172 °C, 180 min, T2a = 180 °C, 120 min, T2b = 180 °C, 240 min, T3a = 200 °C, 95 min, T3b = 200 °C, 180 min, T3c = 200 °C, 265 min, T4a = 220 °C, 120 min, T4b = 220 °C, 240 min, T5 = 228 °C, 180 min; within the same species, means followed by the same letters are not significantly different at $p \leq 0.05$

groups compared with untreated samples (Boonstra & Tjeerdsma 2006, Del Menezzi & Tomaselli 2006). The degradation of thermally less resistant hemicellulose during heat treatment leads to reduced amount of accessible hydroxyl groups and increased proportion of relatively inaccessible crystalline cellulose (Korkut & Hiziroglu 2009). Moreover, crosslinking of the lignin may inhibit the accessibility of free hydroxyl groups to water (Boonstra & Tjeerdsma 2006, Esteves et al. 2008). Therefore, in the same ambient conditions, heat-treated wood absorbs lesser water than control and consequently resulted in lower EMC.

Moisture excluding efficiency

MEE values were derived from EMC and are illustrated in Figure 4. MEE is used to evaluate the hydrophobic or hydrophilic characteristics of wood. MEE for light red meranti and kedondong were 17.90–51.96% and 14.06–54.47% respectively, indicating that the hygroscopicity for both species was greatly reduced by superheated steam treatment. Heat-treated wood has lower hydrophilicity due to the breaking down of hemicelluloses, modifying of lignin, redistributing of wood extractives and decreasing number of hydroxyl groups in wood cell walls (Epmeier & Kliger 2005). Therefore, wood becomes more hydrophobic as the hemicelluloses and amorphous cellulose degrade during heat treatment (Pandey et al. 2016).

Modulus of rupture

Average MOR values for untreated and treated wood samples are illustrated in Figure 5. MOR of the wood reduced with increasing treatment temperature. The effects of heat treatment on bending properties of kedondong were greater than light red meranti because of its higher reduction value, i.e. 63.5 vs. 44.5%. The MOR value of the untreated light red meranti and kedondong wood was 57.01 and 105.88 MPa respectively. The highest reduction in MOR in light red meranti was recorded when the wood was subjected to 220 °C for 240 min (T4a), a reduction of 44.5% compared with that of untreated samples. Meanwhile, kedondong wood experienced the highest reduction of 63.5% when treated at 228 °C for 180 min (T5). These results are in agreement with several studies which reported that bending strength reduced in the heat-treated wood (Johansson & Moren

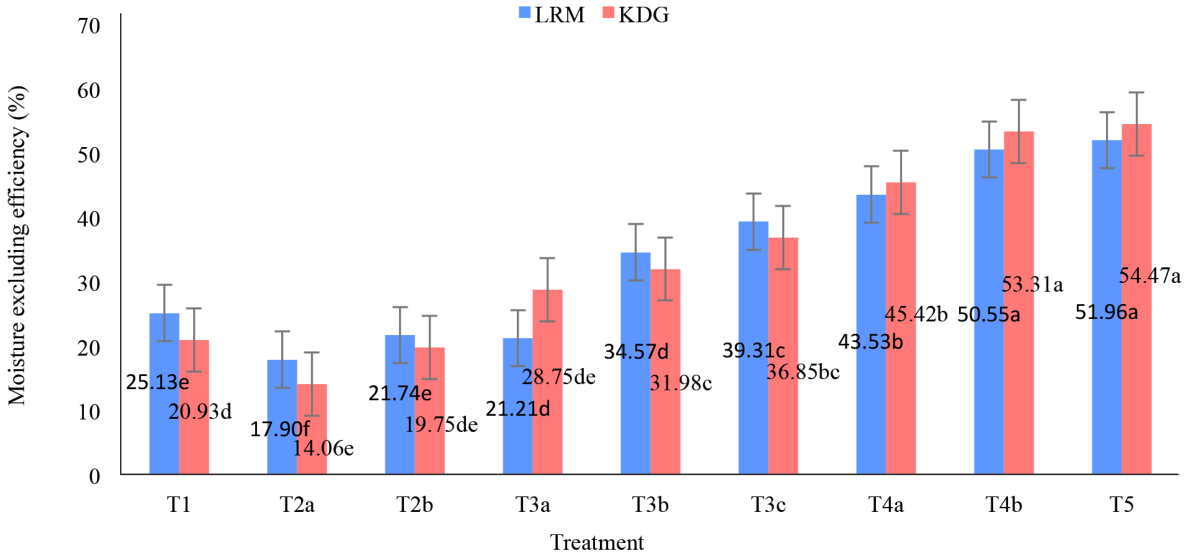

Figure 4 Moisture excluding efficiency of light red meranti (LRM) and kedondong (KDG) wood treated at different temperatures and times; T1 =172 °C, 180 min, T2a = 180 °C, 120 min, T2b = 180 °C, 240 min, T3a = 200 °C, 95 min, T3b = 200 °C, 180 min, T3c = 200 °C, 265 min, T4a = 220 °C, 120 min, T4b = 220 °C, 240 min, T5 = 228 °C, 180 min; within the same species, means followed by the same letters are not significantly different at $p \leq 0.05$

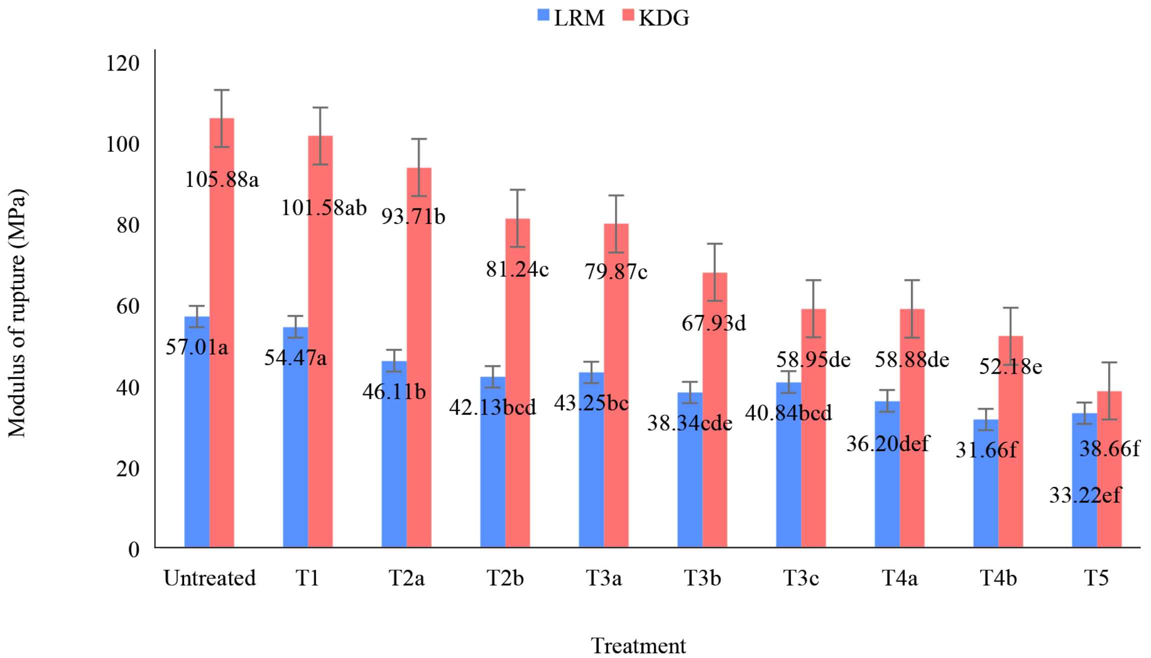

Figure 5 Modulus of rupture of light red meranti (LRM) and kedondong (KDG) wood treated at different temperatures and times; T1 =172 °C, 180 min, T2a = 180 °C, 120 min, T2b = 180 °C, 240 min, T3a = 200 °C, 95 min, T3b = 200 °C, 180 min, T3c = 200 °C, 265 min, T4a = 220 °C, 120 min, T4b = 220 °C, 240 min, T5 = 228 °C, 180 min; within the same species, means followed by the same letters are not significantly different at $p \leq 0.05$

2006, Shi et al. 2007, Korkut et al. 2008). The loss in MOR might be attributed to the degradation of hemicellulose into volatile products and the evaporation of extractives during heat treatment. Relationship between hemicelluloses content and bending strength has been correlated by several researchers (Winandy & Lebow 2001, Esteves et al. 2008). Density loss of the treated wood plays an important role in the reduction of bending strength of the treated wood. The initial density values of the untreated light red meranti and kedondong wood were 393.80 and 619.06 kg m^{-3} respectively. Corresponding to the mass loss, density loss of 4.41 to 10.37% were recorded in heat-treated light red meranti while kedondong wood lost 4.01 to 16.23% of its initial density. Consequently, the bending strength of the heat-treated wood decreased as a function of increasing treatment temperature.

Modulus of elasticity

There was an inconsistent trend of average MOE values of treated and untreated wood samples (Figure 6). MOE of treated light red meranti was found to be lower than that of control samples. Treated kedondong wood showed a similar trend as light red meranti except at T3a (200 °C, 95 min) where it had increased MOE (3.5%) compared with that of control. These findings are in agreement with Shi et al. (2007), Kocaefe et al. (2008) and Kol et al. (2015) where the MOE of treated samples was found to be higher than control when treated in lower treatment severity. Similar to MOR, reduction in MOE is also highly dependent on the density of treated wood. Density loss due to heat-induced mass loss contributes to the reduction in mechanical strength of treated wood (Bal et al. 2014). A direct proportional relationship was observed by the author between wood density and MOE where the MOE decreased as the wood density decreased.

CONCLUSIONS

Heat treatment caused mass loss in wood samples. The wood also displayed reduced EMC and high MEE, indicating that the treated wood was less hygroscopic. Nevertheless, the MOR of the treated wood reduced compared with that of control samples while MOE showed inconsistent results. As treatment temperature and time increased, MOE of treated samples were reduced as well. In conclusion, the present results imply that superheated steam treatment is useful to improve some of the properties of light red meranti and kedondong wood.

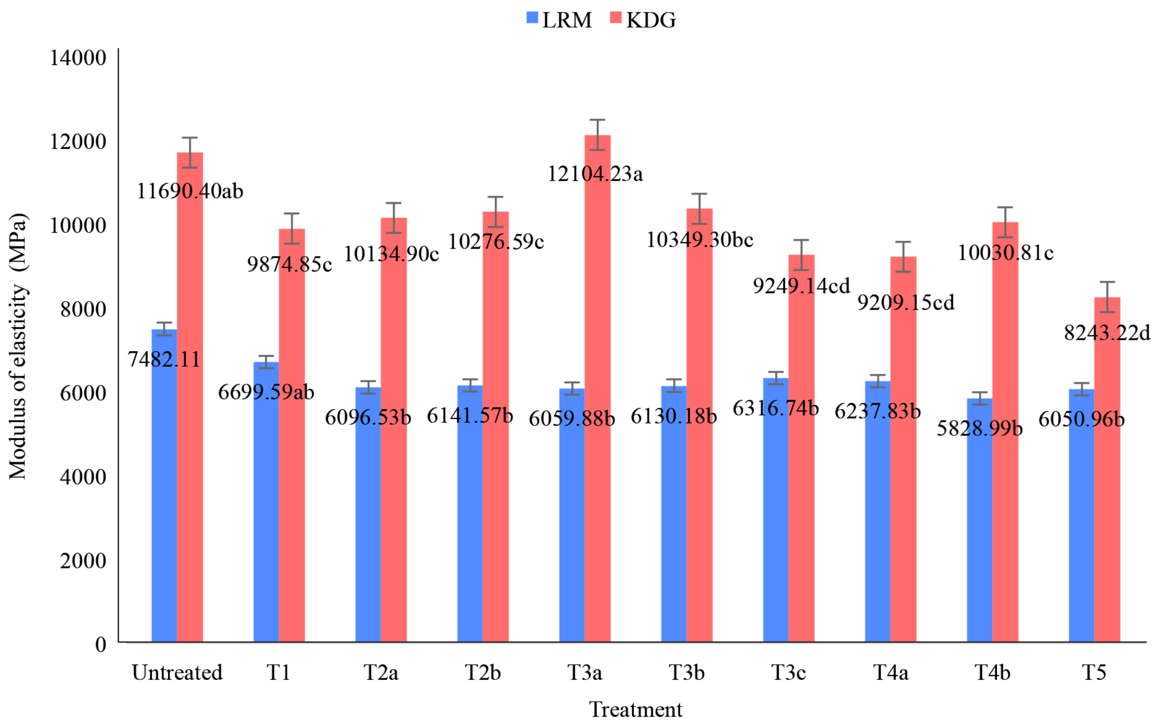

Figure 6 Modulus of elasticity of light red meranti (LRM) and kedondong (KDG) wood treated at different temperatures and times; T1 =172 °C, 180 min, T2a = 180 °C, 120 min, T2b = 180 °C, 240 min, T3a = 200 °C, 95 min, T3b = 200 °C, 180 min, T3c = 200 °C, 265 min, T4a = 220 °C, 120 min, T4b = 220 °C, 240 min, T5 = 228 °C, 180 min; within the same species, means followed by the same letters are not significantly different at $p \leq 0.05$

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