Morphological and bending properties of cross-laminated timber prototype manufactured with densified *Paraserianthes falcataria*

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Abstract. Densification is a modification process commonly used to modify the density and hence, properties improvement of low-density wood. Cross-laminated timber (CLT) manufactured from plantation tree has gained more interest recently but the potentiality of using densified fast-grown plantation wood, Batai (*Paraserianthes falcataria*) in the layering of CLT has yet to be discovered. This study aims to investigate the relationship between morphology of densified wood and bending performance of lab-scale prototype CLT manufactured from it. Laminas after conditioned were hot-pressed (105°C, 6 MPa for 10 minutes) for two stages with venting (press released for 1 minute 40 seconds) in between before cooling to below 100°C to reduce immediate springback. Densified laminas with three different targeted thicknesses (8, 10, and 15) mm were produced before further manufactured into three-layer CLT (24, 30, and 45) mm thick panels. CLT 60 mm thick panels from three pieces of undensified (20 mm) laminas acts as control. Results show that area of pores morphologically had reduced significantly (average 6.59 µm²) for laminas densified to 8 mm. CLT 24 show significant improvement up to 696% (Modulus of Elasticity) and 48.8% (Modulus of Rupture) when the area of pores had reduced. Morphological of densified laminas correlates negatively with bending properties of CLT.

Keywords: Densification; cross-laminated timber; fast-grown plantation wood; morphological; bending.

1. Introduction

One of the engineered timber products that has garnered the eye of the globe these days is the cross-laminated timber (CLT). CLT has been one amongst the new forms of timber that are classified as massive timber today. It was made by gluing the lumber boards that are orthogonally oriented (stacked crosswise in 90°) and therefore the layers of panels were typically in odd numbers with a minimum of three layers of boards [1]. The dimension of the panel is extended through the finger joint technique and widened by combining additional lumber boards in an edgewise direction. Though light-weight materials or low-density wood materials were the choices included in producing CLT panels, the mechanical features in application are still affected by the density itself.

Locally grown plantation timber species, Batai (*Paraserianthes falcataria*) is one of the low-density timber plantations species with average dried weight density of approximately 301 kg/m³. Due to the lower density, Batai is merely appropriate to be made into general utility like furnishings, plywood, lightweight packing materials, etc. [2]. One of the value-added technologies in the research field nowadays is densification, a modification method on the wood materials through mechanical compression in between heated metal plates at suitable temperature, time, and pressure to reduce the thickness and hence, improve the density. Density influences the mechanical properties of wood by
which the void space in the fibre lumens were reduced as a result from mechanical compression at elevated heat and pressure [3]. Although mechanical modification was known for its lower dimensional stability, this method produces chemical-free products which are more environmentally friendly.

However, there is a scarcity of information on the possibilities for mechanically modified wood to be used in engineered wood products. Therefore, this study aims to investigate the relationship between morphology of densified wood and its bending properties of lab-scale CLT prototype manufactured from it.

2. Materials and methods
The sawn, planed, and kiln-dried laminas with dimensions of 300 mm (L) x 50 mm (W) x 20 mm (T) were left to conditioned at 20°C, 65% relative humidity to achieve average moisture content of 12% - 15%. The laminas were then compressed (radial direction) in a hot-pressed machine at 105°C, 6 MPa for 10 minutes [4, 5], with customized metal stoppers of 8 mm, 10 mm, and 15 mm in between the laminas to achieve the targeted thicknesses. Two stages of hot-pressing were performed with a venting stage in between at which the pressure upon the laminas was released for 1 minute 40 seconds before to below 100°C while pressing to reduce immediate springback [6]. Laminas with thickness of 8 mm, 10 mm, 15 mm, and 20 mm (undensified/control) were produced. Subsequently, three small blocks of 5 mm (L) x 5 mm (W) x respective thickness were extracted from each thickness of laminas for morphological examination using Scanning Electron Microscopy (SEM). The changes in area of pores, before and after densification process, were measured using ImageJ software. SEM images were adjusted and calibrated with threshold to distinguish pore and cell wall. After that, Region of Interest (ROI) manager tool were used to obtain measurement for area of pores.

The densified (8 mm, 10 mm, and 15 mm) and undensified/control (20 mm) laminas were then finger-jointed, edge-, and face-glued with 400 g/m² of PVAc glue spread, with each layer of lamination aligned 90° to each other to produce a lab-scale prototype of three-layered cross laminated timber (CLT). Due to the different thicknesses of laminas (8 mm, 10 mm, 15 mm, and 20 mm), three-layered CLT prototype panels with different total thicknesses (24 mm, 30 mm, 45 mm, and 60 mm) were produced, with coding of CLT 24, CLT 30, CLT 45, and CLT 60 respectively. The length and width of all three-layered CLT prototype were 300 mm x 300 mm. 60 mm thick three-layered CLT prototype (CLT 60) manufactured from 20 mm undensified laminas acts as control in this study.

Total test pieces of 30 replicates with dimensions of 300 mm (L) x 300 mm (W) x (24, 30, 45, 60) mm (T) were cut from the three-layered CLT prototype panels. The centre-loading bending strength test was performed using a Universal Testing Machine (UTM) with span length (L) was fixed at 264 mm and testing speed of 3 mm/min, so that the maximum load (P) was obtained within 6 – 20 minutes, as indicated in ASTM D198-05a [7]. Modulus of Elasticity (MOE) and Modulus of Rupture (MOR) were obtained based on equation (1) and equation (2) respectively.

\[
\text{MOE (N/mm}^2\text{)} = \frac{PL^3}{4bd^4\Delta} \\
\text{MOR (N/mm}^2\text{)} = \frac{3PL}{2bd^2}
\]

where, \(P\) is the load below proportional limit (N); \(L\) is the distance between supports / span (mm); \(b\) stands for the width of test piece (mm); \(d\) is the thickness of test piece / depth (mm); \(\Delta\) stands for deflection in corresponding to load \(P\) (mm).

One way ANOVA with post-hoc multiple comparison and Least Significant Different (LSD) was used to analyse and determine the significant difference of morphological (area of pores) between different targeted thickness of densified (8 mm, 10 mm, and 15 mm) and undensified (20 mm) laminas as well as the bending properties of the three-layered CLT prototypes manufactured from those laminas. Relationship between area of pores (morphology) of laminas (densified and undensified) and bending properties of three-layered CLT prototypes were analysed through bivariate Pearson Correlation.
3. Results and discussion

Table 1 show the statistically significant with mean and standard deviation for morphology (area of pores) of densified and undensified laminas, and the bending properties (MOE and MOR) of three-layered CLT prototype manufactured from different targeted thicknesses of laminas. Besides, Figure 1(a) to (d) depicts the morphological examination of densified and undensified laminas through SEM imaging. There were no breaks or fractures in the cell walls of densified laminas (Figures 1(a) to (c)). A crucial aspect in increasing the characteristics of densified wood is the presence of undamaged cell walls [8]. Darwis et al. [9] also noted that densification-induced buckling of cell walls (fibres and vessels) does not result in cracks.

| Targeted thickness of laminas (mm) | Total thickness of three-layered CLT prototype (mm) | Area of pores (µm²) | Bending properties (N/mm²) |
|----------------------------------|-----------------------------------------------|---------------------|----------------------------|
|                                  |                                               |                     | MOE                       |
| 8                                | 24                                            | 6.59 ± (5.98)       | 2348.05 ± (108.74)         |
| 10                               | 30                                            | 11.03 ± (11.97)     | 1348.11 ± (161.28)         |
| 15                               | 45                                            | 67.38 ± (49.76)     | 558.72 ± (115.05)          |
| 20                               | 60                                            | 110.75 ± (95.53)    | 294.94 ± (22.89)           |

Note: Alphabets (a, b, c, and d) inside a column with value in the same column of varied targeted thicknesses for each test indicates significant difference at p ≤ 0.05.

Figure 1. Morphological examination at magnification 800X for, (a) 8 mm densified laminas, (b) 10 mm densified laminas, (c) 15 mm densified laminas, (d) 20 mm undensified laminas.
As the targeted thickness of laminas reduced, the average area of pores decreases. This demonstrates that the fibre and vessel voids have been successfully decreased. The average area of pores/lumen value of the undensified laminas (20 mm) used as a control in this investigation is 110.75 µm². The area of pores was reduced by 39.16%, 90.04%, and 94.05% as the laminas were further densified to 15 mm, 10 mm, and 8 mm, respectively. The findings of this study are comparable to those of Bekhta et al. [10], who found that the compression ratio of wood densification was inversely related to vessel size. When comparing densified laminas of various thicknesses to undensified laminas, statistically significant differences (p ≤ 0.05) are found. This suggests that as laminas are densified to different thicknesses, the pore area in the cell is dramatically reduced. Pore area and porosity are tightly connected, according to Bao et al. [11], with a higher total pore area implying a higher porosity. The decrease of porosity paralleled the increase in density. This study's findings are consistent with those of [11] and [12].

In comparison to CLT 60 (control), the average value of MOE and MOR obtained for CLT 24 tested in a flatwise orientation rose significantly (p ≤ 0.05) by 696.11% and 95.46% respectively. The greater the MOE value, the stiffer the three-layered CLT prototype made from densified laminas are and the less likely they are to bend under force or stress. Furthermore, a higher MOR value allows the material to tolerate a greater amount of stresses while also reducing the risk of bending failure [13]. Aside from that, statistically significant differences (p ≤ 0.05) between three-layered CLT prototype thicknesses in MOE and MOR have been discovered. This shows that increasing the compression ratio of densified laminas from 20 mm to 8 mm thick has a substantial impact on the MOE and MOR of three-layered CLT prototype. Increasing the compression ratio (63%, 98%, and 132%) of surface laminas underwent viscoelastic thermal compression (VTC) densification method increased MOE and MOR of three-layered composites [14].

Besides, Figure 2 and 3 presents the correlation between morphology (area of pores) of densified laminas with MOE and MOR of three-layered CLT prototype as compared to control (undensified). Overall, the area of pores had negative relationship with the bending properties of three-layered CLT prototype. The reduction in pore area (from 20 mm to 8 mm laminas) had a significant negative connection (r = -0.557, p ≤ 0.01) with MOE of three-layered CLT prototype. On the other hand, a medium negative association (r = -0.439, p ≤ 0.01) was found between the area of laminas pores (from 20 mm to 8 mm) in MOR of three-layered CLT prototype. 1) the influence of cell walls moisture content; 2) changes of polymers in cell walls under thermal modification are two possible explanations for the relationship between MOE and MOR (three-layered CLT prototype) and reduction in area of pores (laminas). The MOE of modified laminas can be improved by lowering the cell wall moisture content [15]. Besides, lignin in lamina cell walls is responsible for stiffness, while hemicellulose is responsible for lamina rigidity and brittleness (MOR) [16].

4. Conclusion
Densification had significantly reduced the area of pores (morphology) by 39.16%, 90.04%, and 94.05% in 15 mm, 10 mm, and 8 mm laminas respectively. No damaged cell walls were detected through mechanical densification in this study. Besides, MOE and MOR of three-layered CLT prototype manufactured from 8 mm densified laminas had improved significantly up to 696.11% and 95.46% respectively. Area of pores (morphology) of laminas were negatively correlated with MOE and MOR of three-layered CLT prototype.
5. References

[1] Brandner R 2013 Production and technology of cross-laminated timber (CLT): A state-of-art report In Focus Solid Timber Solutions – European Conference on Cross-laminated Timber (CLT) pp 3-36 University of Bath

[2] Nordahlia A S, Lim S C, Hamdan H and Anwar U M K 2014 Wood properties of selected plantation species: Tectona grandis (Teak), Neolamarckia cadamba (Kelemayan/Laran), Octomeles sumatrana (Binuang) and Paraserianthes falcataria (Batai). Timber Technology Bulletin No. 54. Kepong: Forest Research Institute Malaysia

[3] Zhang Y, Zhang S Y, Chui Y H, Wan H and Bousmina M 2006 Wood plastic composites by melt impregnation: Polymer retention and hardness. Journal of Applied Polymer Science 102 1672-1680

[4] Pelit H, Budakçi M and Sönmez A 2016 Effects of heat post-treatment on dimensional stability and water absorption behaviours of mechanically densified Uludağ Fir and Black poplar woods. BioResources 11(2) 3215-3229
[5] Dogu D, Bakir D, Tuncer D F, Tirak Hizal K, Unsal O and Candan Z 2016 Microscopic investigations of defects in thermally compressed poplar wood panels. *Maderas: Ciencia y tecnología* 18(2) 337-348

[6] Laine K, Segerholm K, Wålinder M, Rautkari I and Hughes M 2016 Wood densification and thermal modification: hardness, set-recovery and micromorphology. *Wood Science and Technology* 50(5) 883-894

[7] ASTM International 2008 D 198-05a Standard test methods of static tests of lumber in structural sizes West Conshohocken PA: ASTM International

[8] Yu Y, Zhang F, Zhu S and Li H 2017 Effects of high-pressure treatment on Poplar wood: Density profile, mechanical properties, strength potential index, and microstructure. *BioResources* 12(3) 6283-6297

[9] Darwis A, Wahyudi I, Dwianto W and Cahyono T D 2017 Densified wood anatomical structures and the effect of heat treatment on the recovery of set. *Journal of Indian Academy of Wood Science* 14(1) 24-31

[10] Bekhta P, Mamnohová M, Sedliačik J and Novák I 2016 Anatomical study of short-term thermo-mechanically densified alder wood veneer with low moisture content. *European Journal of Wood and Wood Products* 74(5) 643-652

[11] Bao M, Huang X, Jiang M, Yu W and Yu Y 2017 Effect of thermo-hydro-mechanical densification on microstructure and properties of Poplar wood (*Populus tomentosa*). *Journal of Wood Science* 63 591-605

[12] Mania P, Wróblewski M, Wójciak A, Roszyk E and Molinski W 2020 Hardness of densified wood in relation to changed chemical composition. *Forests* 11(5) 506

[13] Tan Y F and Liew K C 2019 Morphological behavior of densified low-density plantation wood species: A preliminary study. *Transactions on Science and Technology* 6(3) 316-321

[14] Kutnar A, Kamke F A and Sernek M 2008 The mechanical properties of densified VTC wood relevant for structural composites *Holz Roh Werkst* 66(6) 439-446

[15] Hill C A S 2006 Wood modification: chemical, thermal and other processes Chichester: *John Wiley & Sons Ltd*

[16] Dinwoodie J M 2000 Timber: Its nature and behaviour 2nd (ed) USA: *Taylor & Francis*

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