Correlation between hardness and density profile of glue-laminated timber manufactured from viscoelastic-thermal compression modified *Paraserianthes falcataria* laminas

C M Albert and K C Liew*

Faculty of Tropical Forestry, Universiti Malaysia Sabah, Jalan UMS, 88400 Kota Kinabalu, Sabah, Malaysia

* Corresponding author: liewkc@ums.edu.my

Abstract. A fast-growing tree species, *Paraserianthes falcataria*, possessed low value in density. Therefore, it was subjected to a densification treatment, i.e., viscoelastic-thermal compression (VTC), to enhance its density and mechanical performance. The objective of this study was to investigate the correlation between the density profile and hardness of VTC-modified glue-laminated timber. The laminae underwent VTC, whereby five different pre-steaming durations were applied, ranging from 0-30 minutes prior to forming into glue-laminated timber panels. The panels were cut into pre-determined test pieces and subjected to density determination using an X-ray densitometer and hardness test in the tangential direction using the ball indentation method. The correlation analysis found that increasing density slightly enhanced the hardness of the tangential surface of the glue-laminated timber test pieces, whereby the Pearson's correlation values, $r$ were .074 (0 minutes, non-densified), .154 (0 minutes, densified), -.027 (10 minutes, densified), .088 (20 minutes, densified), and .225 (30 minutes, densified). Nevertheless, the associations were found to be statistically insignificant because the p-values were greater than 0.05, thus suggesting densification treatment did not enhance hardness.

Keywords: Densification; viscoelastic-thermal compression; *Paraserianthes falcataria*; glue-laminated timber.

1. Introduction

Mechanical properties of wood are commonly correlated with its density. It is possible to compress wood with densification treatment to achieve desired properties. The densification technology was first implemented on wood over 100 years ago when a hydraulic press set at 140° C, and 25 MPa was used to compress wood to produce densified wood products such as "Lignostone" [1,2]. Thermo-mechanical (TM), thermo-hydro mechanical (THM), and viscoelastic-thermal compression (VTC) are three common types of densification treatments which have all been applied to improve the mechanical characteristics of wood [1-5]. Thermo-mechanical (TM) is a method of producing dimensionally stable densified wood with optimal characteristics by combining pre-heating, compression via hot-pressing, and post-heat treatments [2,3]. Thermo-hydro mechanical (THM) treatment, which heavily relies on high-pressure steam injection, is a commonly utilized densification method in which wood is compressed in a closed chamber with high temperature saturated vapour [4]. VTC (viscoelastic-thermal compression) is a densification method that combines pre-steaming (softening) and hot-pressing to achieve densification without damaging the cellular structure of compressed wood [5-7].

The ability of a steel ball to penetrate the wood surface is used to determine the hardness of the wood [8,9]. One of most widely used hardness evaluating technique was the Brinell hardness method, which applied on EN 1534 and JIS Z 2101 standards [8]. The Janka hardness test, detailed in ASTM D
143 standards, is another standard approach for analyzing the hardness of wood materials [9]. Paraserianthes falcataria, also known as Batai wood, was classified as a light hardwood species with an average density of 360 kg/m$^3$ [7]. Glue-laminated timber comprises several layers of laminas glued together in a similar parallel direction, with at minimum three layers [8]. The aim of this study was to evaluate the correlation between the density profile and hardness of VTC-modified glue-laminated timber manufactured from Paraserianthes falcataria laminas.

2. Materials and methods

2.1 Viscoelastic-Thermal Compression (VTC) treatment
Paraserianthes falcataria laminas with the dimension of 20mm (thickness) x 50mm (width) x 300mm (length) were subjected to VTC treatment. The pre-steaming process was carried out using a steamer machine. The laminas were pre-steamed for three different time durations, ranging from 10-30 minutes, as displayed in Table 1.

| Parameter | Pre-steaming duration (minute) | Pre-steaming temperature (°C) | Pressing Pressure (MPa) | Phases during densification |
|-----------|-------------------------------|-------------------------------|------------------------|-----------------------------|
| NS/ND (control) | - | - | - | - |
| NS/D | 10 | 100 | 6 | 10 minutes pressing + 100 seconds venting phase + 10 minutes pressing + 5 minutes annealing phase |
| S1/D | 20 | 100 | 6 | pressing + 100 seconds venting phase + 10 minutes |
| S2/D | 30 | 100 | 6 | |

Note: NS/ND (non-pre-steamed, non-compressed); NS/D (non-pre-steamed, compressed); S1/D (10 minutes pre-steamed, compressed); S1/D (10 minutes pre-steamed, compressed); S2/D (20 minutes pre-steamed, compressed); S3/D (30 minutes pre-steamed, compressed)

The laminas were then transited to the hot-press machine for densification, which consisted of six phases. Target thickness was set to 10mm. The VTC modified laminas were trimmed, sanded, and glued together to form glue-laminated timber panels with the dimension of 30mm (thickness) x 50mm (width) x 300mm (length).

2.2 Density profile measurement
The glue-laminated timber panels were cut into a total of 30 test pieces with a size of 30mm (thickness) x 50mm (width) x 50mm (length). An X-ray densitometer (Figure 1) was used for density profile measurement. Upon completion of the test, a density profile graph was displayed on the computer.
2.3 Hardness test

For the hardness test, the glue-laminated timber panels were cut into a total of 30 test pieces with a size of 30mm (thickness) x 50mm (width) x 150mm (length). The procedures were carried by referring to ASTM 143-08. Universal testing machine equipped with polished steel ball was used for this test (Figure 2). Maximum load (N) values were obtained upon completion of 5.5 mm depth penetration.

![Polished steel ball](image)

Figure 2. Universal testing machine equipped with polished steel ball.

2.4 Data analysis

Data analysis was carried out by using one-way ANOVA, whereby post-hoc LSD test was performed for multiple comparison purpose. The correlation analysis was performed by using Pearson’s correlation coefficient.

3. Results and discussion

3.1 Density profile

The result for both density profile and hardness tangential were displayed in Table 2. Based on the statistical analysis in Table 2, S2/D have the highest density profile mean value of 547.99 kg/m$^3$, followed by S1/D (527.89 kg/m$^3$), S3/D (505.19 kg/m$^3$), NS/D (488.19 kg/m$^3$), and control (NS/ND) with lowest mean value of 272.86 kg/m$^3$. S2/D was statistically significant from control and NS/D; however, it was no different from S1/D and S3/D.

| Parameter        | Density Profile (kg/m$^3$) | Hardness (N)       |
|------------------|----------------------------|--------------------|
| NS/ND (control)  | 272.86 ± (23.89)           | 689.98 ± (147.01)  |
| NS/D             | 488.19 ± (75.32)           | 1859.49 ± (303.18) |
| S1/D             | 527.89 ± (84.54)           | 1724.75 ± (493.70) |
| S2/D             | 547.99 ± (75.53)           | 2095.77 ± (597.67) |
| S3/D             | 505.19 ± (66.78)           | 2034.00 ± (286.72) |

*a* Numbers with no parentheses are the value of means.

*b* Subscript alphabets a, b, c, and d represent the significant differences between parameters.

*c* Numbers after “±” and in parentheses are the standard deviations value.
Figure 3. Variation of density throughout thickness of glue-laminated timber manufactured from VTC modified *Paraserianthes falcataria* laminas.

Unpenetrated adhesive would have been the main factor for the sudden peak attained between different layers, as shown in Figure 3. Prior studies on wettability properties of VTC modified *Paraserianthes falcataria* laminas suggested that highly viscous adhesive such as Polyvinyl Acetate (PVAc) might require a longer period to be diffused inside the laminas; due to the high viscosity value of the adhesive itself, as well as poor wettability properties of the densified laminas [5, 7, 8]. Furthermore, earlier study suggested that low-density zones have higher void area/open vessels, whilst high-density regions have collapsed vessels [5]. Previous study on anatomy property of *Paraserianthes falcataria* found that cell lumens of control (NS/ND) were not collapsed, with cell lumen area mean value of 157.43 µm²; minor fractures were observed on the lumens of NS/D (119.19 µm²) and S1/D (89.78 µm²), while significant deformation rate was observed on S2/D (69.36 µm²) and S3/D (39.61 µm²) [5]. This finding explained why untreated laminas have a lower density profile mean value than treated laminas, and also why the density value suddenly drops at a specific point.

3.2 Hardness (tangential)

Tangential plane of glue-laminated timber possessed better resistance properties to withstand elastic deformation, after the laminas were subjected to VTC. Result for hardness test in tangential direction demonstrated that S2/D to have the highest mean value of maximum load (2095 N), followed by S3/D (2034.00 N), NS/D (1854.00 N), S1/D (1724.75 N), and control (NS/ND) with lowest mean value of 689.98 N. Based on statistical comparison in Table 2, S2/D had a significant difference with all parameters except for S3/D. Irregular trend of result might be influenced by variation of extractive contents and different regions of wood that being processed into samples, as suggested by previous studies on densification [1,4,6].

3.3 Correlation analysis

Correlation analysis was performed to evaluate the relationship between density profile and hardness (tangential) of glue-laminated timber from each parameter (Table 3). The relationship strength was categorized into very strong positive (+.70 → +1), strong positive (+.40 → +.69), moderate positive (+.30 → +.39), weak positive (+.20 → +.29), slight/negligible positive (+.01 → +.19), none (0),
slight/negligible negative (-.01 → -.19), weak negative (-.20 → -.29), moderate negative (-.30 → -.39), strong negative (-.40 → -.69), and very strong negative (-.70 → -1).

Table 3. Pearson’s correlation between hardness (tangential) and density obtained from density profile of glue-laminated timber.

| Parameter     | Pearson’s Correlation, *r* | Sig. (2-tailed) |
|---------------|----------------------------|-----------------|
| Control (NS/ND) | .074                       | .901            |
| NS/D          | .154                       | .415            |
| S1/D          | -.027                      | .887            |
| S2/D          | .088                       | .644            |
| S3/D          | .225                       | .231            |

*a*. Correlation is significant at the 0.05 level (2-tailed).

**b**. Correlation is significant at the 0.01 level (2-tailed).

Figure 4. Correlation between hardness (tangential) and density obtained from density profile of glue-laminated timber manufactured from VTC modified Paraserianthes falcataria laminas.

Based on the results displayed in Table 3 and Figure 4, a small positive association was discovered between hardness (tangential) and density profile of control (NS/ND), with *r* value of *r*(28) = .074, *p* < .901). This result indicated that increasing density slightly influenced the resistance of the tangential plane of glue-laminated timber to deformation. For NS/D, the *r* value was *r*(28) = .154, *p* < .415, indicating an insignificant, weak positive association. This outcome showed that the hardness (tangential) value increased as the density increased, however, this correlation was not valid as it was not significant. Furthermore, a small negative relationship was identified between hardness in tangential (T) direction and density profile (glulam) of S1/D, with *r* value of *r*(28) = -.027, *p* < .887, which indicated density had negligible influence on the improvement of hardness (tangential) of glue-laminated timber. This particular relationship was not statistically significant, as the *p*-value was greater than 0.05.

Hardness (tangential) and density profile of S2/D, on the other hand, were found to have a slight positive association, with *r* value of *r*(28) = .088, *p* < .644. This finding also revealed that an increase in the density had a negligible effect on increasing the hardness (tangential) value of glue-laminated timber.

The relationship between the hardness (tangential) and density profile of S3/D was weak and negative, with *r* value of *r*(28) = .225, *p* < .231. The result showed that increasing the value of lamina
density increased the hardness (T) of glulam. However, because there were insufficient statistical evidence due to p-values greater than 0.05, all the associations above were not statistically significant.

4. Conclusion

Based on mean values, viscoelastic-thermal compression (VTC) treatment enhanced the density and hardness of glue-laminated timber manufactured from laminas of *Paraserianthes falcataria*. In terms of statistical comparison, glue-laminated timber of S1/D was found to have significant difference with all other parameters; while S2/D was statistically different from all parameters except for S3/D. The correlation analysis between density profile and hardness (tangential) indicated that density had a negligible effect on improving the hardness of glue-laminated timber. Despite that, all the relationships were statistically insignificant. Hence, viscoelastic-thermal compression (VTC) treatment did not improve the hardness (tangential) of glue-laminated timber.

5. References

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