JURNAL UPI

Indonesian Journal of Science & Technology

Journal homepage: http://ejournal.upi.edu/index.php/ijost/

IJoST Indonesian Journal of Science & Technology

Fire Performance of Cross-Laminated Timber Enhanced by Borax Treatment and Densification for Structural Wood Composites

*Kang Chiang Liew**, *Noel Fowler Norbert, Rafidah Md. Salim*

Universiti Malaysia Sabah, Sabah, Malaysia

*Correspondence: E-mail: liewkc@ums.edu.my

ABSTRACT

This study investigates the fire performance of Cross-Laminated Timber (CLT) using a combination of densification and borax treatment to enhance its safety for structural applications. Laminated Batai wood underwent borax treatment either before or after densification, followed by tests on absorption capacity and combustion resistance. The results revealed variations in fire resistance and density profiles depending on the treatment sequence. Densification increased density, and borax improved flame retardancy. The treatment order influenced absorption rates and charring behavior because the densification process modified internal porosity, affecting chemical penetration. Image analysis and thermal evaluation confirmed that specific combinations improved fire performance. This approach offers a scientific and technological basis for optimizing fire-resistant engineered wood products with lightweight species.

ARTICLE INFO

Article History:

Submitted/Received 15 Apr 2025
First Revised 20 May 2025
Accepted 13 Jul 2025
First Available Online 14 Jul 2025
Publication Date 01 Dec 2025

Keyword:

Borax treatment,
Cross-laminated timbe,
Densification,
Fire performance,
Paraserianthes falcataria.

1. INTRODUCTION

Wood remains a widely used construction material due to its strength-to-weight ratio, ease of processing, and renewable nature. Many reports regarding woods have been well-documented [1-4]. However, its inherent flammability limits its use in structural applications, particularly in high-risk fire zones [5,6]. The increasing use of engineered wood products, such as Cross-Laminated Timber (CLT), in sustainable architecture necessitates improvements in fire performance to meet building safety codes [7,8]. Various strategies, such as surface coatings, chemical impregnation, and mechanical densification, have been explored to enhance wood's resistance to fire and extend its utility [9,10]. Densification mechanically compresses wood, reducing porosity and increasing density, which limits oxygen penetration and the spread of combustion [11,12]. Likewise, fire-retardant chemicals like borax alter the chemical pathways of combustion, promoting char formation and reducing flammable gas release [13,14].

Combining densification with borax treatment introduces a promising route to improve fire performance, especially in fast-growing and lightweight tropical species such as Paraserianthes falcataria (Batai). While borax application alone improves fire resistance, its interaction with densified wood is complex. Densification may hinder borax diffusion due to reduced pore space, whereas borax pretreatment could interfere with the compression process [15,16]. Previous studies have explored these treatments independently, but limited research has examined the effect of their sequence on borax absorption, density, and fire resistance [17,18]. Understanding how treatment order impacts material behavior is crucial for developing high-performance CLT panels suitable for tropical regions. The application of scientific and technological principles, including microstructural analysis and controlled thermal testing, enables the characterization of how densification and chemical loading influence fire-retardant properties.

Therefore, this study aims to evaluate the fire performance of CLT panels made from Batai wood by analyzing the effect of borax treatment before and after densification on absorption and combustion resistance. The novelty lies in examining how the sequencing of these treatments alters physical and thermal responses in engineered timber, providing new insight into optimizing treatment strategies for tropical hardwoods. This research contributes to the development of safer, eco-friendly, and structurally robust wood composites aligned with sustainable construction practices.

2. METHODS

Batai wood (*Paraserianthes falcataria*) was selected as the raw material. A total of 360 Batai laminas were randomly chosen to ensure sample representativeness. CLT panels (300 mm length x 300 mm width x 60/30 mm thickness) were produced and subsequently cut into test pieces (223 mm length x 146 mm width). The study aimed to investigate the effect of borax treatment (before and after densification) on borax absorption and its influence on fire performance.

2.1. Borax Treatment and Densification

A 10% concentration of borax has been deemed suitable for boric acid production [19]. The borax was prepared at a ratio of 9:1 water to borax solution. Hot water and a stirrer were used to dissolve the borax.

DOI: https://doi.org/10.17509/ijost.v10i3.87837
p- ISSN 2528-1410 e- ISSN 2527-8045

The laminas were completely submerged in the prepared 10% borax solution. Every 24 hours, the laminas were carefully removed from solution, excess surface moisture was eliminated using absorbent paper towels, and their weights were measured using the digital balance. This process was repeated for a predetermined period until the borax absorption reached equilibrium, indicated by the constant weight reading for at least two consecutive measurements. Borax absorption percentage was calculated using Equation (1).

$$Absorption\ (\%) = \frac{Wet\ weight - Original\ weight}{Original\ weight} \times 100\% \qquad (1)$$

The laminas were air-dried after treatment by open-air stacking using stick spacers between the laminas. The weight of each lamina was measured again using a digital balance every 24 hours throughout the drying process. This continues until a constant weight is achieved. The weight data will be used to calculate the drying rate and moisture content reduction over time. The reduction in the weight of the wooden lamina was then calculated using Equation (2).

$$Drying\ percentage\ (\%) = \frac{Q-W}{Q} \times 100\% \qquad (2)$$

where Q is the weight before stacking (g) and W is the weight after stacking (g)

After the borax treatment, the densification process was conducted to a 10 mm thickness from 20 mm, which is a 50% compression ratio, as per the method outlined by previous studies [17]. The lamina was compressed using the hot-press machine at 105°C and 6 MPa pressure, maintaining the pressure for 3 minutes and resting 1 minute and 40 seconds, and repeating the step 2 times before the next pressing. After that, then compress again for 1 minute with heat before the cooling process (heat off) for 5 minutes. **Table 1** shows the treatment groups implemented in this study.

Table 1. Treatment groups in this study.

Treatment Group	Description
NT (Control)	No treatment
DNB	Densification with no borax
BND	Borax with no densification
DB	Densification after borax
BD	Borax after densification

2.2. Preparation of CLT Test Piece

The laminas from different treatment groups stated in **Table 1** were glued together with Tech-bond L560s adhesive at 250 g/m2 glue spread to form a single layer according to previous studies [20]. Then, additional layers were stacked on top with the grain running perpendicular (at a 90-degree angle) and glued together to create a three-layer CLT panel. The laminas were arranged in a CLT with dimensions 300 mm (length) x 300 mm (width) x 60/30 mm (thickness). Once the CLT was obtained, it was cut into test pieces with dimensions of 223 mm (width) x 146 mm (length) for the fire performance test, as illustrated in **Figure 1**.

DOI: https://doi.org/10.17509/ijost.v10i3.87837
p- ISSN 2528-1410 e- ISSN 2527-8045

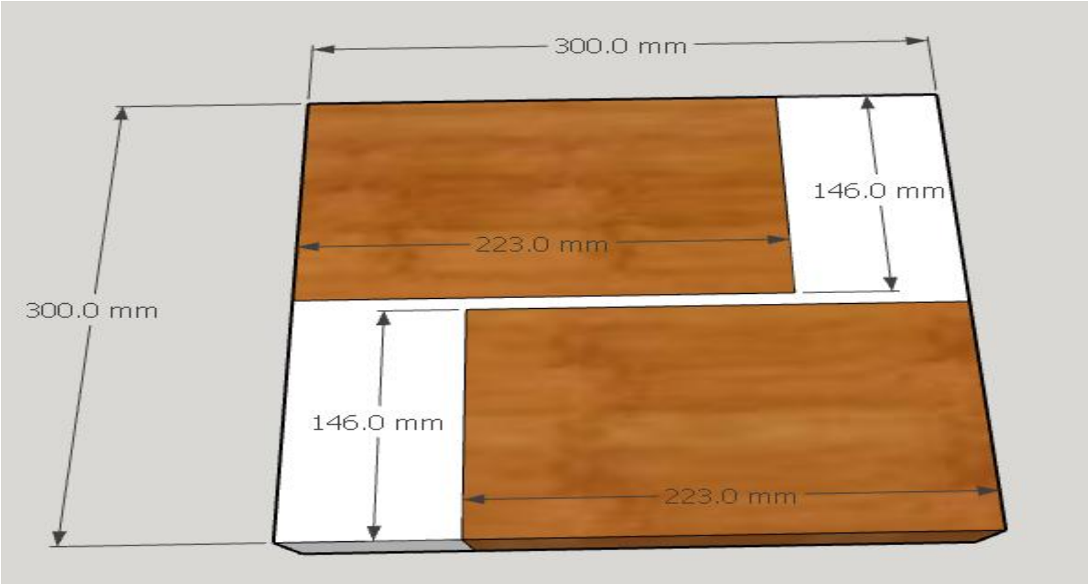


Figure 1. . Cutting design for fire testing [20].

2.3. Determining the Physical Properties of Lamina and CLT

Physical properties evaluate moisture content and density using the ASTM standard for lamina samples, and the EN standard for CLT panels with minor modifications.

2.3.1. Moisture Content

Moisture content was determined using the oven-dry method according to ASTM D4442 (Method B) with slight modifications. For laminas, 20 mm Batai cubes (three replicates) were obtained and dried in an oven at 103 ± 2°C for 24 hours, or obtain a constant weight was obtained. For CLT panels, test pieces measuring 50 mm width x 50 mm length x 60/30 mm (depending on the thickness of the treatment group) were used following the guidelines of EN 13182-1. In both cases, they were placed in a desiccator for 15 minutes before final weighing. Moisture content was calculated using Equation (3).

$$MC\ (\%) = \frac{AD-OD}{OD} \times 100\% \quad (3)$$

Where MC is moisture content (%), AD is original air-dry mass (g), and OD is oven-dry mass (g)

2.3.2. Density

Density was determined according to ASTM D2395-17 (Test Method A) for laminas and EN 323 for CLT panels, with minor modifications. Using a digital balance and calliper, the mass and dimensions of 20 mm Batai cubes for lamina, and 50 mm width x 50 mm length x 60/30 mm (depending on the thickness of the treatment group) for CLT, were measured. Three replicates were used for each parameter. Density (kg/m^3) was calculated by dividing mass (kg) and volume (m^3).

2.4. Fire Performance Test

The apparatus for the fire resistance test is based on the specifications outlined in **Figure 2** for NIST Voluntary Product Standard PS 1-09, with some slight adjustments. This setup involved exposing the CLT samples to an open flame. Three test specimens were prepared for each specific parameter to be tested. Before testing commences, the moisture content of each CLT panel was measured, and the values ranged from 10.06% to 15.10%.

DOI: https://doi.org/10.17509/ijost.v10i3.87837
p- ISSN 2528-1410 e- ISSN 2527-8045

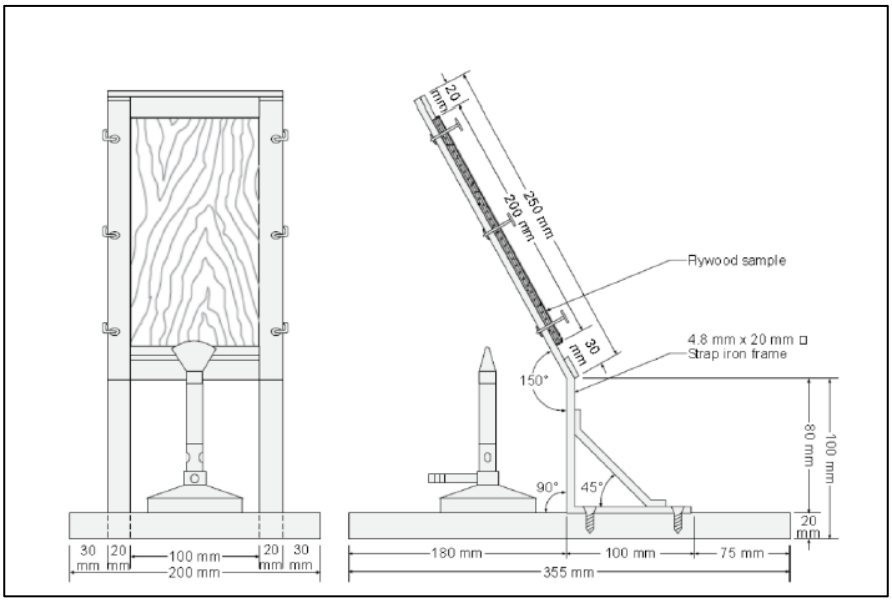
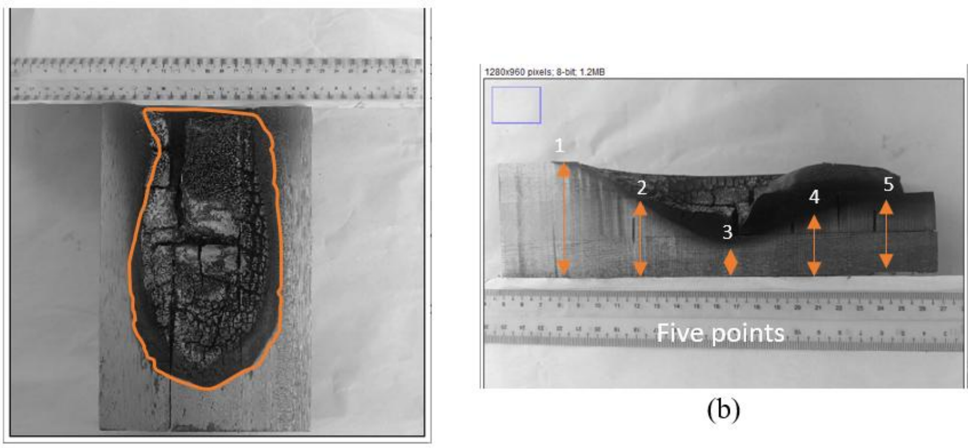


Figure 2. Apparatus setup for fire test according to NISTD Voluntary PS (PS1-09) [21].

2.5. Image Analysis

Image analysis was performed using the previous method [21]. For image analysis, the test specimens in this experiment, both the top and side views of each piece, were captured using a standard phone camera. These images were then uploaded and analysed with image analysis software called ImageJ. The primary aim of this image analysis was to quantify the extent of charring, focusing on both the charred area and depth. To assess the mass loss area and char depth, digital images were captured and analysed using ImageJ software. The images were first uploaded and then converted to 8-bit for both the top and side views. A known length scale was used for image calibration to ensure accurate measurements. To calculate the charred area, ImageJ's built-in area measurement tool was employed. Optimal threshold values were visually determined to distinguish the charred areas from the unexposed wood. The wand (tracing) tool was used to select the charred areas in **Figure 3(a)**, which were then added to the ROI manager to obtain the measurements. Char depth was measured from the original surface to the char boundary using the side view at five different points as seen in **Figure 3(b)**.



(a) (b)

Figure 3. Image of test piece set to 8-bit; (a) Top view, (b) Side view.

DOI: https://doi.org/10.17509/ijost.v10i3.87837
p- ISSN 2528-1410 e- ISSN 2527-8045

Mass loss was determined by comparing the initial and final sample weights. The Mass Loss Rate (MLR) was calculated by dividing the mass loss by the total burn time, and the Charring Rate (CR) was calculated by dividing the char depth by the burning duration (2 hours). The data obtained were exported to a CSV file for further analysis, using separate equations to calculate the MLR and CR using Equations (5) and (6), respectively.

$$Mass\ Loss\ Rate\ (MLR) = \frac{mi - mf}{As} \tag{5}$$

where MLR is mass loss rate (g/m^{2}s), mi is initial mass (g), mf is final mass (g), A is total exposed surface area (m^2), and s is duration of exposure (s).

$$Charring\ Rate\ (\beta 0) = \frac{Dcharr}{t} \tag{6}$$

where β0 is the charring rate (mm/min), Dchar is the average char depth (mm) from the side view, and t is the duration of exposure (min).

2.6. Data Analysis

Data was analyzed using Statistical Package for the Social Sciences (SPSS) software. Descriptive statistics, including mean and standard deviation, were calculated for all variables. To assess the effects of densification and borax treatment on borax absorption and density, one-way ANOVA was conducted. The five treatment groups stated in **Table 1** (NT, DNB, BND, DB, and BD) were compared using a post-hoc Least Significant Difference (LSD) test at a significance level of p≤0.05.

3. RESULTS AND DISCUSSION

3.1. Physical Properties

Table 2 shows that group DB achieved the highest MC (15.10%). Conversely, the lowest MC was recorded for DNB (10.06 %). For the density, DNB has the highest density among all the groups. The lowest density was observed in the BND groups (391.21 kg/m³). The densifications and borax treatment have a significant effect on the density.

Table 2. Mean values of moisture content (%) of laminas and density (%) for CLT for different treatments.

Treatment Group	Moisture content (%) ± SD	Density (kg/m^3) ± SD
NT (Control)	$11.59_a \pm 0.11$	$351.87_a \pm 3.28$
DNB	$10.06_b \pm 0.02$	$580.24_b \pm 10.06$
BND	$14.09_c \pm 0.45$	$391.21_c \pm 3.50$
DB	$15.10_d \pm 0.01$	$437.46_d \pm 10.32$
BD	$12.24_e \pm 0.10$	$526.54_e \pm 8.83$

* Different subscript letters indicate a significant difference between the various treatment groups at p ≤ 0.05 using one-way ANOVA LSD post hoc.

* Standard deviation (SD), No treatment (NT), densification with no borax (DNB), borax with no densification (BND), densification after borax (DB), borax after densification (BD).

The MC of DNB groups showed that densification reduced MC slightly, due to reduced void spaces within the wood, which limits moisture absorption [18]. This reduction could also be attributed to the compression of the wood fibers during densification [22], decreasing overall porosity and thus restricting moisture absorption. Meanwhile, BND treatment increased moisture content due to borax typically introduces additional chemicals into the wood structure, attracting and holding water molecules [23]. Borax treatment increases the wood's MC due to the hygroscopic nature of borax, which attracts and retains water [24,25]. This confirms that borax treatment increased the MC when applied to the CLT.

DOI: https://doi.org/10.17509/ijost.v10i3.87837
p- ISSN 2528-1410 e- ISSN 2527-8045

For DB, the overall MC is the highest because the borax treatment significantly raises the moisture content, even after densification. For BD, the woods absorb moisture initially, and subsequent densification reduces the MC, but it remains higher than the control. The BD groups show lower MC than the DB groups due to the densification process after borax treatment causes some of the borax to leach out (**Figure 4**).

Figure 4. Lamina that treated with borax when compressed.

Referring to **Table 1**, the increased density from DNB groups can be attributed to the physical compression of the wood, reducing its volume without significantly affecting its mass. Thus, it is due to the densification that successfully compressed the wood fibers, resulting in a heavier material per unit volume [26]. For BND groups, it had a variable effect on density, with a slight increase in both lamina and CLT samples. This could be due to borax infiltrating the wood structure [27,28], adding mass but altering internal bonding, especially in the more complex CLT structure. The reduction in density in some cases might also be due to the borax causing some structural degradation or weakening of the wood fibres, thus reducing its overall compactness [29,30].

Applying borax after densification (DB group) leads to a slightly lower density compared to densification alone can potentially be attributed to the swelling effect of the borax on the previously densified. In the process of borax treatment, the densified lamina thickness increased by about 62.31%. When the densified lamina is soaked in borax, it absorbs water along with borax chemicals. Water absorption can cause wood fibres to swell slightly. This swelling can contribute to an increase in the overall thickness of the lamina, even if the densification process was successful, compressing the wood structure to some extent [31,32]. If densification effectively compressed the wood fibres' structure in the DB group, subsequent borax treatment with its water content might lead to some counteracting swelling. This increase indicates that while densification improves compactness. The subsequent borax treatment does not further increase the density due to its distribution within the already compacted wood fibres [31]. Interestingly, the BD group showed an increase in density compared to the control groups. This is because when borax treatment is applied before densification, the borax particles are better distributed and locked within the compressed wood structure. This leads to more uniform and compact materials, resulting in increasing density values [33,34].

3.2. Absorption Properties of Borax

Figure 5 illustrates the relationship between borax absorption by the lamina and the duration of the soaking process. Both the before and after densification exhibit an increase in borax absorption as the soaking time increases. The rate of absorption appears to slow down after a certain period. However, there is a difference between the lamina in absorption rates.

DOI: https://doi.org/10.17509/ijost.v10i3.87837
p- ISSN 2528-1410 e- ISSN 2527-8045

The densified lamina (borax after densification) soaked up about a quarter (24%) of the borax, and it took 14 days (139.47%) for the weight to become constant. The lamina that did not densify initially takes only 9 days (58.52 %) to become constant.

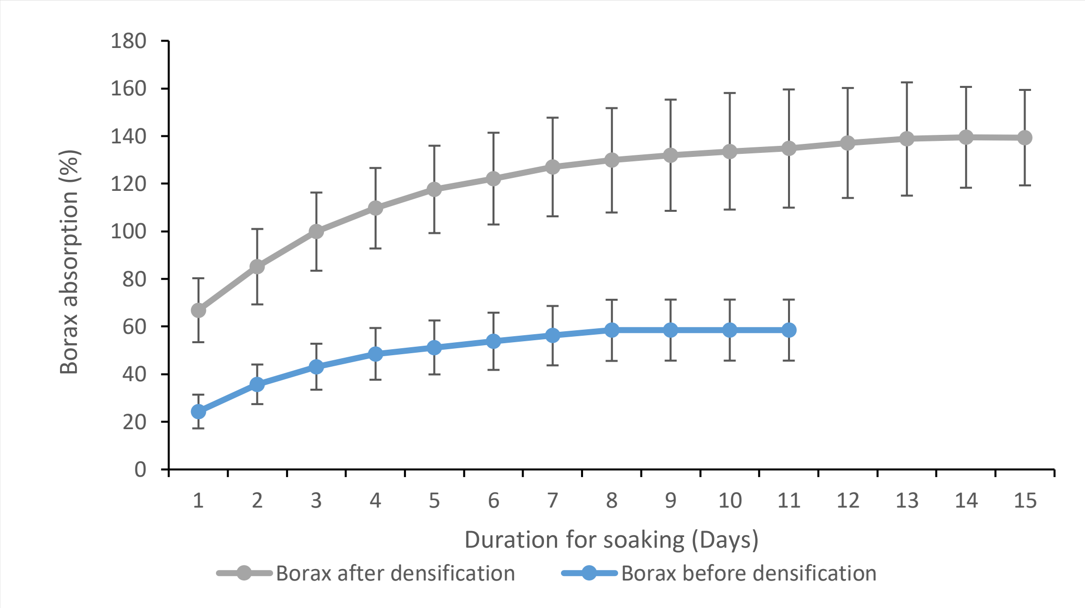


Figure 5. Percentage of borax absorption by the lamina (%).

The lamina treated borax before densification demonstrated a rapid initial borax uptake, then a phase of progressive plateauing. This behavior suggests that the accessible pore structure in the untreated lamina facilitated rapid borax diffusion. As the soaking progressed, available sorption sites became increasingly occupied, leading to a deceleration in the absorption rate. This phenomenon is consistent with previous studies, indicating that wood reaches a saturation point for borax uptake [35].

In contrast, the lamina subjected to densification before borax treatment showed a noticeably slower initial absorption rate. This compression process likely reduced the pore volume and altered the lamina microstructure, hindering the initial penetration of borax molecules. According to previous studies [36], densification can impede the diffusion into the compressed wood. It eventually reaches a saturation level comparable to that of the untreated lamina [37].

3.3. Fire Performance

Understanding the fire behavior of wood composite panels is crucial for their safe application. This study investigates fire performance through mass loss rate (MLR) and charring rate (CR) analysis.

Figure 6 shows MLR analysis conducted on five different treatment groups. The results show that group BD has obtained the highest MLR (1.0482 g/m2s), followed by DNB (0.6115 g/m2s), DB (0.4384 g/m2s), BND (0.3808 g/m2s), and NT (0.3632 g/m2s). Statistically significant differences between the groups, with BD showing highly significant differences from other group treatments. BND demonstrated that the most effective MLR reduction. The DNB group was significantly different from BND, BD, and NT due to variations in material properties and treatments. Group DNB has a higher MLR than group BND, indicating that its characteristics or treatments make it more prone to mass loss. BND treatment appears to be the most effective in reducing the MLR of the wood composite panels among the parameters.

DOI: https://doi.org/10.17509/ijost.v10i3.87837
p- ISSN 2528-1410 e- ISSN 2527-8045

The combination of borax and densification BD and DB did not provide additional benefits compared to borax treatment alone.

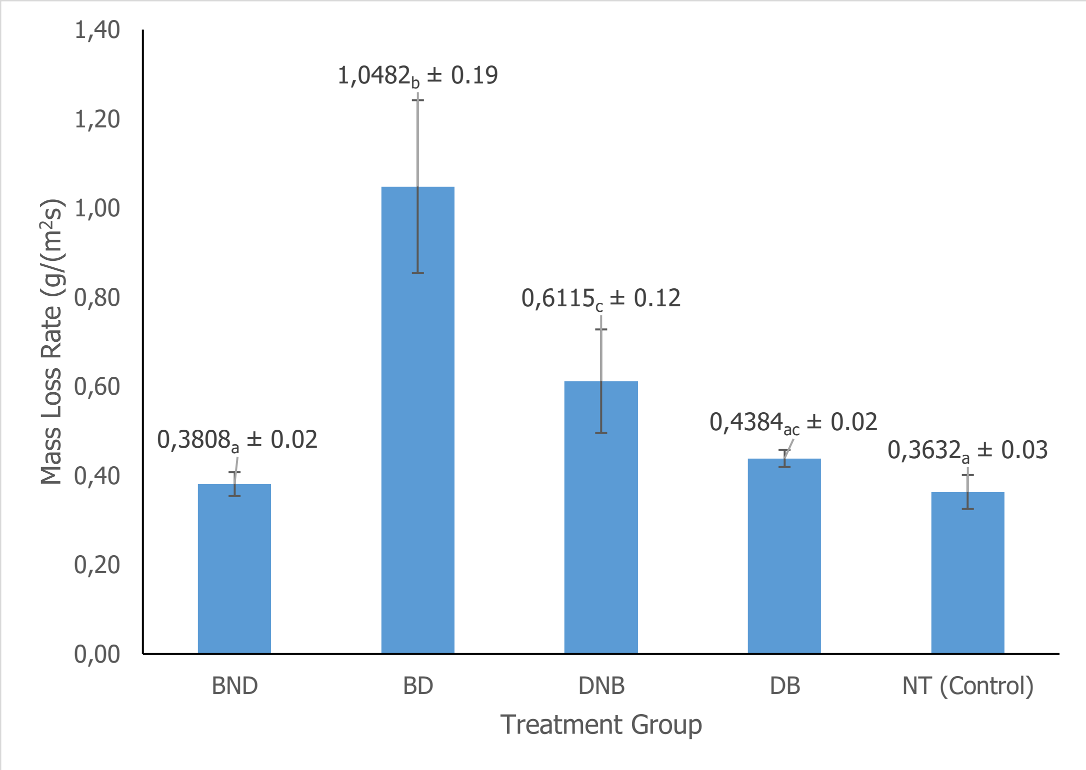


Figure 6. Mass Loss Rate (g/m 2 s) for different treatment groups. Error bars indicate standard deviation. Note: * Different subscript letters indicate a significant difference between the various conditions for each treatment group. Each treatment group was significantly different ($p < 0.05$) using one-way ANOVA followed by LSD post hoc. Error bars indicate standard deviation. * No treatment (NT), densification with no borax (DNB), borax with no densification (BND), densification after borax (DB), borax after densification (BD).

The BND group demonstrated the most effective MLR reduction, suggesting that borax treatment alone can significantly improve the fire performance of wood composite panels. (Wu & Xu, 2014). Borax is renowned for its fire-retardant properties, as it forms a protective char layer on the wood surface, inhibiting the release of flammable gases and slowing down the combustion process [38]. Conversely, the DNB group showed a higher MLR than BND. While densification improves wood density and strength, it also reduces porosity, potentially limiting borax penetration and reducing the formation of a protective char layer [39]. The increased density in DNB implies a larger combustible mass per unit volume, contributing to a higher MLR during combustion.

The elevated MLR of the BD group can be attributed to compromised interfacial adhesion between layers. The sequence of borax treatment followed by densification likely resulted in a disrupted wood structure. Borax impregnation, followed by the densification process, might have created voids or weakened the wood fibers, hindering effective adhesive penetration during panel assembly. Consequently, reduced adhesive bonding contributed to accelerated mass loss during fire exposure. In contrast, the DB groups started with densification, followed by borax treatment. The initial densification process compacted the wood structure, potentially creating a more favorable surface for adhesive bonding. Subsequent borax treatment, despite including swelling (62.31 %), did not appear to significantly compromise the adhesive bond [40]. Upon air-drying, the water evaporates, leaving the borax within the

DOI: https://doi.org/10.17509/ijost.v10i3.87837
p- ISSN 2528-1410 e- ISSN 2527-8045

wood structure [41]. This improved interfacial adhesion contributed to enhanced fire resistance and a lower MLR.

For the charring rate (**Figure 7**), the BD group attained the highest charring rate (0.3214 mm/min), followed by NT (0.2072 mm/min), BND (0.2061 mm/min), DNB (0.1863 mm/min), and DB (0.1736 mm/min). All parameters achieved the allowable charring rate, which is 0.50 mm/min for solid/laminated wood composite with a density of more than 450 kg/m^3. Statistically, the BD group showed significantly higher charring rates compared to all other groups. The DB group exhibited the lowest charring rate, significantly different from BD. No significant differences were observed among BND, DNB, and NT groups.

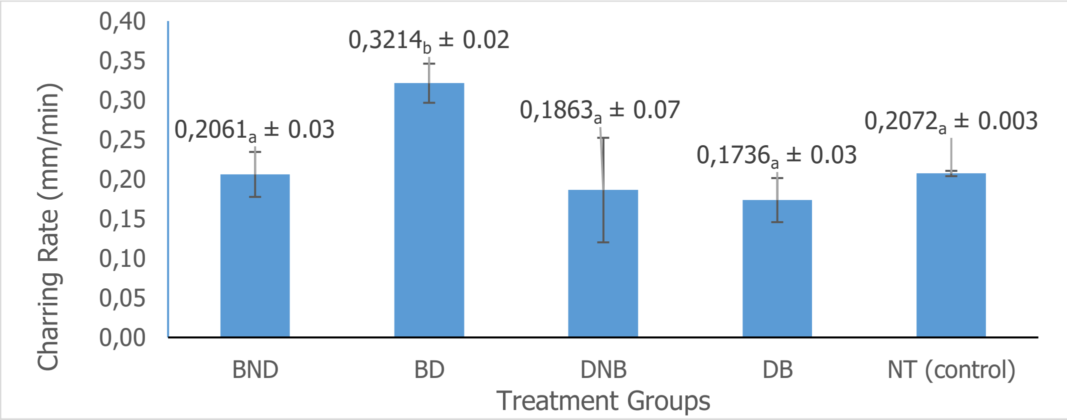


Figure 7. Charring rate for different treatments group. Error bars indicate standard deviation. Note: * Different subscript letters indicate a significant difference between the various conditions for each treatment group. Each treatment group was significantly different ($p < 0.05$) using one-way ANOVA followed by LSD post hoc. Error bars indicate standard deviation. * No treatment (NT), densification with no borax (DNB), borax with no densification (BND), densification after borax (DB), borax after densification (BD).

The analysis reveals that the order of applying the borax and densification treatment significantly affects the CR of the wood composite panels. The borax applied before densification (BD) could potentially react with the wood components. BD groups suggest that applying the borax before densification might have facilitated deeper penetration of the fire-retardant agent into the wood structure, possibly resulting in a stronger catalytic impact on the formation of char [42].

In contrast, the DB groups have the lowest CR, indicating that densification first, followed by borax application creates a different composition that hinders charring [43]. Densification might compact the wood fibres, making it harder for them to burn and char, and the subsequent borax application might not be able to fully penetrate the denser material [34]. The BND and DNB groups, representing the individual effects of borax and densification, respectively, exhibited no significant difference in charring rates and temperature profile. This confirms that both treatments contribute to fire resistance, albeit to a lesser extent than their combined application in the DB groups.

4. CONCLUSION

This study showed that densification considerably decreased borax absorption into the lamina of Batai wood. The synergistic impact of densification and borax treatment resulted in increased fire resistance. These findings indicate that the combination of densification and borax treatment can successfully improve the fire performance of CLT. Furthermore, the

DOI: https://doi.org/10.17509/ijost.v10i3.87837
p- ISSN 2528-1410 e- ISSN 2527-8045

study showed that the duration of borax treatment, whether before or after densification (BD or DB), had a substantial impact on the resultant density of the lamina. The densification produces higher density. Adding borax before densification produced an increased final density than applying it after densification. This shows that the order in which these treatments are performed changes the physical properties of the wood. Overall, the fire performance of CLT was significantly improved by combining densification and borax treatment (DB groups). The treated CLT had a longer time for burning and a lower heat release rate than the untreated control samples, suggesting the efficacy of these treatments in improving fire resistance. However, it is still necessary to adjust the treatment technique to achieve a compromise between improved fire performance and the preservation of other crucial material attributes, such as mechanical strength and durability.

5. ACKNOWLEDGMENT

We would like to express our sincere gratitude to Universiti Malaysia Sabah for providing the facilities and Primbumi Sdn. Bhd. for the adhesive.

6. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. The authors confirmed that the paper was free of plagiarism.

7. REFERENCES

[1] Nurjamil, A.M., Wolio, N.A., Laila, R.N., Rohmah, S.A., Nandiyanto, A.B.D., Anggraeni, S., and Kurniawan, T. (2021). Eco-friendly batteries from rice husks and wood grain. *ASEAN Journal of Science and Engineering*, *1*(1), 45-48.

[2] Olabiyi, O.S. (2024). Efficacy of open learning system on college of education students' achievement in woodwork technology. *Indonesian Journal of Educational Research and Technology*, *4*(1), 9-22.

[3] Nurjamil, A.M., Wolio, N.A., Laila, R.N., Rohmah, S.A., Anggraeni, S., and Nandiyanto A.B.D. (2021). Effect of rice husks and wood grain as electrolyte adsorbers on battery. *Indonesian Journal of Multidiciplinary Research*, *1*(1), 69-72.

[4] Hidayah, F., Muslihah, F., Nuraida, I., Winda, R., Vania, V., Rusdiana, D., and Suwandi, T. (2021). Steam power plant powered by wood sawdust waste: A prototype of energy crisis solution. *Indonesian Journal of Teaching in Science*, *1*(1), 39-46.

[5] Wimmers, G. (2017). Wood: a construction material for tall buildings. *Nature Reviews Materials*, *2*(12), 1-2.

[6] Kodur, V., Kumar, P., and Rafi, M. M. (2020). Fire hazard in buildings: review, assessment and strategies for improving fire safety. *PSU Research Review*, *4*(1), 1-23.

[7] Erdinç, S. Y. (2023). A timeless journey of strength and beauty: The potentials of the use of stone in architecture. *Journal of Design for Resilience in Architecture and Planning*, *4*(3), 317-338.

[8] Mallo, M. F. L., and Espinoza, O. A. (2014). Outlook for cross-laminated timber in the United States. *BioResources*, *9*(4), 7427-7443.

[9] Erbaşu, R., and Țăpuşi, D. (2020). Considerations about fire behaviour of an unprotected wood elements according to Romanian Code SR EN 1995-1-2-2004. In *IOP Conference Series: Materials Science and Engineering*, *789*(1), 012019.

DOI: https://doi.org/10.17509/ijost.v10i3.87837
p- ISSN 2528-1410 e- ISSN 2527-8045

[10] 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.

[11] Cabral, J. P., Kafle, B., Subhani, M., Reiner, J., and Ashraf, M. (2022). Densification of timber: a review on the process, material properties, and application. *Journal of Wood Science*, *68*(1), 20.

[12] Tenorio, C., Moya, R., and Navarro-Mora, A. (2021). Flooring characteristics of thermo-mechanical densified wood from three hardwood tropical species in Costa Rica. *Maderas. Ciencia y Tecnología*, *23*, 1-12.

[13] Aslan, S., and Özkaya, K. (2004). Farkli kimyasal maddelerle emprenye edilmiş ahşap esasli levhalarin yanma mukavemetinin araştirilmasi. *Turkish Journal of Forestry*, *5*(2), 122-140.

[14] Xu, Z., Zhao, W., Yan, L., Tang, X., Feng, Y., and Wang, Z. (2023). Processing of Pinus sylvestris L. into a heat-insulating, thermally stable, and flame-retarded material by combining the flame-retardant impregnation and densification treatment. *Holzforschung*, *77*(10), 762-775.

[15] Augustina, S., Wahyudi, I., Darmawan, I. W., Malik, J., Basri, E., and Kojima, Y. (2020). Specific gravity and dimensional stability of boron-densified wood on three lesser-used species from Indonesia. *Journal of the Korean Wood Science and Technology*, *48*(4), 458-471.

[16] Chu, D., Mu, J., Avramidis, S., Rahimi, S., Liu, S., and Lai, Z. (2019). Functionalized surface layer on poplar wood fabricated by fire retardant and thermal densification. Part 1: Compression recovery and flammability. *Forests*, *10*(11), 955.

[17] Albert, C. M., and Liew, K. C. (2022). Influence of densification treatment on the morphology and density profile of Paraserianthes falcataria Laminas. *Philippine Journal of Science*, *151*, 2509-2516.

[18] Liew, K. C., Albert, C. M., and Shamsuddin, E. O. (2023). Physical and morphological changes in heat-treated and densified fast-growing timber material. In *E3S Web of Conferences*, *445*, 01009.

[19] Mergen, A., Demirhan, M. H., and Bilen, M. U. R. A. T. (2003). Processing of boric acid from borax by a wet chemical method. *Advanced Powder Technology*, *14*(3), 279-293.

[20] Tan, Y. F., and Liew, K. C. (2022). Morphological and bending properties of cross-laminated timber prototype manufactured with densified Paraserianthes falcataria. In *IOP Conference Series: Earth and Environmental Science*, *1053*(1), 012033.

[21] Brandon, D., Klippel, M., and Frangi, A. (2021). Glueline integrity in fire. *RISE Research Institutes of Sweden*, *107*(6), 1–79.

[22] Bao, M., Huang, X., Zhang, Y., Yu, W., and Yu, Y. (2016). Effect of density on the hygroscopicity and surface characteristics of hybrid poplar compreg. *Journal of Wood Science*, *62*(5), 441–451.

[23] Mendis, M. S., Ishani, P. A. U., and Halwatura, R. U. (2023). Impacts of chemical modification of wood on water absorption: a review. *Journal of the Indian Academy of Wood Science*, *20*(1), 73–88.

[24] Lesar, B., Gorišek, Ž., and Humar, M. (2009). Sorption properties of wood impregnated with boron compounds, sodium chloride, and glucose. *Drying Technology*, *27*(1), 94–102.

[25] Yu, Y., Jiang, X., Ramaswamy, H. S., Zhu, S., and Li, H. (2018). Effect of high-pressure densification on moisture sorption properties of Paulownia wood. *BioResources*, *13*(2), 2473–2486.

DOI: https://doi.org/10.17509/ijost.v10i3.87837
p- ISSN 2528-1410 e- ISSN 2527-8045

[26] Feng, T. Y., and Chiang, L. K. (2020). Effects of densification on low-density plantation species for cross-laminated timber. In *AIP Conference Proceedings*, *2284*(1), 020001.

[27] Bagheri, S., Alinejad, M., Ohno, K., Hasburgh, L., Arango, R., and Nejad, M. (2022). Improving durability of cross laminated timber (CLT) with borate treatment. *Journal of Wood Science*, *68*(1), 34.

[28] Khalil, H. P. S. A., Dungani, R., Mohammed, I. A., Hossain, M. S., Sri Aprilia, N. A., Budiarso, E., and Rosamah, E. (2014). Determination of the combined effect of chemical modification and compression of agatis wood on the dimensional stability, termite resistance, and morphological structure. *BioResources*, *9*(4), 6614-6626.

[29] Adanur, H., Fidan, M. S., and Yaşar, Ş. Ş. (2017). The technological properties of oriental beech (Fagus orientalis Lipsky) impregnated with boron compounds and natural materials. *BioResources*, *12*(1), 1647–1661.

[30] Toker, H., Baysal, E., Simsek, H., Senel, A., Sonmez, A., Altinok, M., Ozcifci, A., and Yapici, F. (2009). Effects of some environmentally-friendly fireretardant boron compounds on modulus of rupture and modulus of elasticity of wood. *Wood Research*, *54*(1), 77–88.

[31] Augustina, S., Wahyudi, I., Darmawan, I. W., Malik, J., Basri, E., and Kojima, Y. (2020). Specific gravity and dimensional stability of boron-densified wood on three lesser-used species from Indonesia. *Journal of the Korean Wood Science and Technology*, *48*(4), 458-471.

[32] da Silva Lins, T. R., Silva, T. C., Araujo, E. C. G., and da Rocha, M. P. (2022). Brocas marinhas e a biodeterioração da madeira no Brasil: uma revisão sistemática. *Nativa*, *10*(4), 495-505.

[33] Chu, D., Mu, J., Avramidis, S., Rahimi, S., Liu, S., and Lai, Z. (2019). Functionalized surface layer on poplar wood fabricated by fire retardant and thermal densification. Part 1: Compression recovery and flammability. *Forests*, *10*(11), 955.

[34] Scharf, A., Švajger, Č., Lin, C.-F., Humar, M., Sandberg, D., and Jones, D. (2024). Effect of fire-retardant treatment of wood before thermo-mechanical densification. *Wood Material Science & Engineering*, *19*(3), 790–793.

[35] Willerding, A. L., and Vianez, B. F. (2003). Borax diffusion treatment in the preservation of sumauma (Ceiba pentandra (L.) Gaertn.) veneer. *Revista Arvore*, *27*(3), 321–326.

[36] Neyses, B., Peeters, K., Buck, D., Rautkari, L., and Sandberg, D. (2021). In-situ penetration of ionic liquids during surface densification of Scots pine. *Holzforschung*, *75*(6), 555–562.

[37] Yokoyama, M. T., Spence, C., Hengemuehle, S. M., Whitehead, T. R., von Bernuth, R., and Cotta, M. (2016). Sodium tetraborate decahydrate treatment reduces hydrogen sulfide and the sulfate-reducing bacteria population of swine manure. *Journal of Environmental Quality*, *45*(6), 1838–1846.

[38] Gan, W., Chen, C., Wang, Z., Song, J., Kuang, Y., He, S., Mi, R., Sunderland, P. B., and Hu, L. (2019). Dense, self-formed char layer enables a fire-retardant wood structural material. *Advanced Functional Materials*, *29*(14), 1807444.

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

[40] Harada, T., Miyatake, A., Kamikawa, D., Hiramatsu, Y., Shindo, K., Inoue, A., Miyamoto, K., Tohmura, S., Hatano, Y., and Miyabayashi, M. (2013). Temperature dependence of adhesive strength and fire resistance of structural glued laminated timber beams. *Mokuzai Gakkaishi*, *59*(4), 219–226.

DOI: https://doi.org/10.17509/ijost.v10i3.87837
p- ISSN 2528-1410 e- ISSN 2527-8045

[41] Suchy, M., Virtanen, J., Kontturi, E., and Vuorinen, T. (2010). Impact of drying on wood ultrastructure observed by deuterium exchange and photoacoustic FT-IR spectroscopy. *Biomacromolecules*, *11*(2), 515–520.

[42] Kurt, R., and Mengeloglu, F. (2008). The effect of boric acid/borax treatment on selected mechanical and combustion properties of poplar laminated veneer lumber. *Wood Research*, *53*(2), 113–120.

[43] Wang, Z., Gao, Y., Zhou, Y., Fan, C., Zhou, P., and Gong, J. (2023). Pyrolysis and combustion behaviors of densified wood. *Proceedings of the Combustion Institute*, *39*(3), 4175–4184.

DOI: https://doi.org/10.17509/ijost.v10i3.87837
p- ISSN 2528-1410 e- ISSN 2527-8045