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IDENTIFICATION OF MATERIALS AND BONDING PARAMETERS FOR CROSS-LAMINATED PANELS MADE IN ASIA

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ABSTRACT: This study identifies suitable fast-growing bio-based materials and optimal bonding parameters for cross-laminated timber (CLT) panels manufactured in Asia. A systematic literature review, integrated with a multi-criteria decision analysis, evaluates adhesives and structural performance—bending strength, stiffness, and bond-line shear—of candidate species such as bamboo, palm, and various tropical timbers. Adhesive bond quality and mechanical properties of CLT panels are compiled from recent research emphasizing Southeast Asian species. An analytic hierarchy process model was developed, attributing specific criteria weights derived from the analysis: density (10%), timber modulus of elasticity(30%), and timber bending strength (60%). Results indicate Bambusoideae (bamboo) and fast-growing hardwoods, including Gmelina arborea, Acacia mangium, and Anthocephalus cadamba (jabon), meet structural requirements. Palm-based panels significantly underperform due to inherent bonding issues and low fiber strength. The study highlights one-component polyurethane and phenol-resorcinol-formaldehyde as optimal adhesives. The study's findings provide practical insights to support local CLT production in Southeast Asia using indigenous materials and optimized bonding conditions.

KEYWORDS: Cross-laminated timber, bonding parameters, tropical hardwoods, bamboo, analytic hierarchy process.

1 – INTRODUCTION

Engineered massive wood panels such as cross-laminated timber (CLT) are increasingly popular as sustainable construction materials. CLT consists of layers of boards bonded perpendicular to each other, forming stiff, load-bearing panels suitable for structural use [1]. While CLT traditionally utilizes softwoods (e.g., spruce, pine) from temperate regions, there is growing interest in Asia to produce CLT using fast-growing local species. Southeast Asia has abundant plantations of fast-growing hardwoods (e.g., Acacia, Eucalyptus, Gmelina, Hevea) and non-timber species like bamboo and palm [2]. Using these local resources can reduce reliance on imports, promote sustainable forestry, and add value to under-utilized biomass [3]. However, differences in wood anatomy and chemistry pose challenges for adhesive bonding and structural performance.

Adhesive bonding quality is critical, as glue lines must resist shear and delamination under service conditions. International standards specify minimum rolling shear strength and sufficient wood failure in bonded joints [4]. Conventional CLT adhesives such as polyurethane (PUR), phenol-resorcinol-formaldehyde (PRF), melamine-urea-formaldehyde (MUF), and emulsion polymer isocyanate (EPI) may perform differently on tropical substrates [1,2]. Studies indicate MUF provides highest shear strength for laminated bamboo, outperforming PUR and EPI [5]. For palm, PUR performs best but still yields relatively low shear strengths [6]. Achieving durable bonds requires optimizing pressure, spread rate, and surface preparation [7].

Another consideration is the mechanical performance of CLT made from new species. Key properties include panel bending strength, which includes modulus of rupture (MOR) and modulus of elasticity (MOE), as well as rolling shear strength governed by the weaker cross-layers [8]. Fast-growing juvenile woods often have lower density and shorter fibers, which can reduce strength and stiffness relative to mature softwoods [8].

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Nonetheless, recent research on species like Falcataria moluccana, Anthocephalus cadamba, Acacia mangium, and Hevea brasiliensis shows that, with proper adhesives, CLT from these species can meet structural demands [1,3]. This paper compiles data from multiple studies on adhesives, panel mechanical properties, and bonding parameters to guide future CLT manufacturing in Southeast Asia. A multi-criteria approach using the analytic hierarchy process (AHP) is introduced to rank materials based on bending, stiffness, and bond-line shear performance. This leads to the development of an AHP model with established weights for timber properties that be used to predict the performance of cross-laminated panels.

2 – BACKGROUND

2.1 ADHESIVE BONDING REQUIREMENTS AND PERFORMANCE

Adhesive bond strength and durability are paramount for CLT panel integrity. Traditional phenolic adhesives like PRF and MUF, as well as one-component PUR, have been widely used [4]. PRF is known for high durability but requires longer press times, while PUR cures faster and is formaldehyde-free. Both can produce strong bonds in softwood CLT: Sikora et al. [4] reported PUR-bonded spruce laminations had higher initial shear strength, whereas PRF-bonded samples had lower delamination (better durability) under cyclic humidity. Press pressures of about 0.6 MPa are commonly sufficient [4,7].

For tropical hardwoods, both PRF and PUR can satisfy CLT bond criteria, but performance is diverese. Acacia mangium CLT bonded with PRF showed slightly higher bending strength and stiffness than PUR-bonded panels [7]. PRF bonds exhibited deeper resin penetration, leading to greater moisture resistance. PUR, though flexible, sometimes failed at the glue line under load [7]. For bamboo-based laminates, adhesive selection is even more critical. Xing et al. [5] found MUF provided the highest shear strength (~5 MPa) for cross-laminated bamboo, whereas EPI was ineffective. PVA also performed well on bamboo scrimber, but typically lacks the durability for exterior conditions [5]. Palm wood is an extreme case: even the best adhesives produce relatively low bond strengths (≤0.8 MPa), reflecting palm's fibrous, non-homogeneous structure [6,9]. Overall, adhesives must be matched to the wood's anatomy; for example, dense bamboo may need ~1.0 MPa press to achieve adequate penetration, while moderate pressures (0.6–0.8 MPa) suffice for typical hardwoods [5].

2.2 MECHANICAL PROPERTIES OF CLT FROM FAST-GROWING ASIAN SPECIES

The viability of a species for CLT depends on the finished panel's bending strength (MOR), stiffness (MOE), and bond-line shear strength. Many fast-growing species can yield MOR above 30 MPa in CLT form, meeting or exceeding standard structural requirements [1,3]. For instance, rubberwood CLT reached 25–35 MPa bending strength [1], while Acacia mangium CLT reached ~35–40 MPa [7]. Eucalyptus can reach 40–45 MPa [3]. Bamboo is capable of 63–90 MPa in cross-laminated panels [5], surpassing many conventional timbers. In contrast, palm-based CLT seldom exceeds 3–5 MPa [9,10], reflecting weak bonding and low fiber strength. Sengon and jabon (density ~300–450 kg/m³) can produce ~30–40 MPa CLT bending strength but often exhibit lower stiffness (MOE ~6–8 GPa) and bond-line shear ~2.0–2.6 MPa [3]. Hybrid or mixed-species approaches can improve performance, such as combining a stronger outer lamella with a lighter core [1,3]. Summaries of these data form the basis for a multi-criteria ranking in the next sections.

3 – PROJECT DESCRIPTION

A systematic review of literature published since 2010 was conducted, focusing on cross-laminated panels made from tropical Asian species: bamboo, palm, coconut, rubberwood, acacia, eucalyptus, dipterocarps, sengon, jabon, and gmelina. Key properties were extracted:

- Timber-level properties: density, static MOE, bending MOR.

- CLT panel performance: panel MOR (bending strength), panel MOE (bending stiffness), bond-line shear strength.

- Adhesive parameters: type (PUR, PRF, MUF, etc.), pressing pressure, any reported shear or delamination test results.

Data were standardized (e.g. MPa, kg/m³) and tabulated, with references. The main performance criteria for final ranking of species were: (1) CLT bending strength, (2) CLT MOE, (3) bond-line shear. Each criterion was deemed essential for structural viability of a panel. A complementary analysis mapped how base timber properties (density, timber MOE, timber MOR) might predict those panel-level results.

4 – EXPERIMENTAL SETUP

Selecting suitable materials for cross-laminated timber (CLT) construction demands objective decision-making, incorporating multiple, often conflicting criteria such as mechanical properties, sustainability, and durability. This complexity requires a structured method of assessment. One effective approach is the Analytic Hierarchy Process (AHP), a multi-criteria decision-making (MCDM) tool commonly applied to resolve complex selection problems in construction [11, 12].

The AHP methodology facilitates decision-making through a structured hierarchy and quantifiable comparisons. It comprises four fundamental steps: defining the hierarchical problem structure, establishing decision-maker preferences, checking preference matrix consistency, and generating the final ranking [13,14].

In the first step, the decision problem is defined clearly, establishing a hierarchical structure comprising the primary goal (optimal material selection for CLT), critical evaluation criteria (panel bending strength, modulus of elasticity (MOE), and bond-line shear), and the available material alternatives (such as bamboo, palm wood, rubberwood, Chinese fir, etc.). This hierarchical decomposition allows systematic assessment of alternatives at various levels, enhancing transparency and clarity in decision-making [12].

The second step involves the definition of relative preferences for the identified criteria by pairwise comparisons. Preferences are assigned numeric values on a 1–9 scale, where '1' denotes equal importance, '3' slightly greater importance, '5' clearly greater importance, '7' significantly greater importance, and '9' extreme importance [12]. Intermediate even numbers (2,4,6,8) represent intermediate preferences.

From the pairwise comparisons, a square matrix (A) is constructed. Matrix terms (a_{ij}) reflect relative importance between criteria, with diagonal elements being unity ($a_{ii}=1$) and reciprocal relationships ($a_{ij}=1/a_{ji}$). Normalization of matrix A into a matrix B is performed through the following equation:

$$b_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}}, \quad (1)$$

The weights (w_i) for each criterion are then derived as arithmetic means of rows in normalized matrix B [12,13]:

$$w_i = \frac{1}{n}\sum_{j=1}^{n} b_{ij}, \quad (2)$$

In the third step, consistency of the preferences is verified through Consistency Index (CI) and Consistency Ratio (CR), computed as:

$$CI = \frac{\lambda_{max} - n}{(n-1)}, \quad (3)$$

$$CR = \frac{\lambda_{max} - n}{RI \cdot (n-1)}, \quad (4)$$

where λmax is the maximum eigenvalue of matrix A, and RI is a Random Index dependent on matrix dimension n [12]. If $CR \leq 0.10$, the matrix is deemed consistent, ensuring reliability of results.

In the final step, alternatives (timber species) are evaluated and ranked based on the aggregate scores calculated by multiplying criteria weights (w_i) by corresponding performance metrics (k_i). The overall priority or composite score (P) for each alternative is calculated as follows [12]:

$$P = \sum_{i=1}^{n} w_i \cdot k_i \quad (5)$$

5 – RESULTS

5.1 SUMMARY OF MATERIAL PROPERTIES

Table 1 compiles the key data from the references on both timber-level and CLT-level properties, along with adhesive bonding insights. The table is arranged by species, with columns for density, MOE, MOR (timber), CLT bending strength, CLT MOE, bond-line shear, and typical bonding parameters.

Table 1: Modelary *data on materials performance*

Material	Density (kg/m³)	Timber MOE (MPa)	Timber MOR (MPa)	CLT MOR (MPa)	CLT MOE (MPa)	Bond-line Shear (MPa)	Optimal Adhesive	Press Pressure (MPa)	References
Bamboo (Grass)	600–800	10000–13000	90–150	63–90	9000–12000	2.5–3.2	MUF, PVA	0.6–1.0	[5, 15]
Date Palm Frond (Palm)	400–700	6000–9000	40–60	0.9–2.8	~1000	0.5–1.5	PUR, Epoxy	0.6–0.8	[6,9,10,16]
Rubberwood (HW)	600–799	7900–8500	50–80	25–35	7000–8000	2.6–4.5†	PUR	0.4–0.6	[1, own data]
Coconut (Palm)	600–999	5000–9500	35–75	15–40	5000–9000	0.8–1.6	PUR	0.8	[1,17]
Acacia (HW)	650–700	9000–11000	80–100	30–40	10000–12000	1.2–1.6	PRF	0.8	[2,7]
Eucalyptus (HW)	700–800	9000–12000	70–90	35–45	11000–13000	2.5-3.0†	PUR	0.4–0.6	[18, 19, 20, own data]
Dipterocarp (HW)	600–750	7500–10500	40–70	20–30	8000–9000	1.0–1.5	PRF	0.8	[3, 21]

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Chinese Fir (SW)	350–450	7000–9500	30–50	15–25	7000–8000	0.8–1.2	PUR	0.6	[22]
Korean Larch (SW)	500–600	8000–10000	40–60	20–35	8000–9000	1.2–1.4	PRF	0.8	[23]
Balsa (SW)	100–200	3000–4000	10–15	8–12	2000–3000	0.96–2.50	PUR	0.6	[24]
Sengon (HW)	300–400	6000–8000	30–40	15–25	6000–7000	~2.2	PUR	0.6	[2,3, 25]
Jabon (HW)	400–450	7000–8500	45–60	35–40	8000–9000	~2.6	PUR	0.6	[2,3]
Gmelina (HW)	450–480	8000–9000	60–65	25-35	7000-8000	3.1-3.4	PUR, EPI, Epoxy	0.6–0.8	[26, 27]

Note: HW = Hardwood, SW = Softwood. A dash (–) indicates data not reported. Where a range is shown, it references multiple adhesives. Where a single value is shown, it references the best-performing adhesive from that study. †Unpublished experimental data generated by the authors.

Bamboo (dens. 600–800 kg/m³) stands out with exceptionally high timber strength (MOR 90–150 MPa) and yielded the highest reported CLT bending strength (63–90 MPa). Its estimated panel MOE (9–12 GPa) is also high, matching dense hardwoods. Acacia (650–700 kg/m³) and eucalyptus (700–800 kg/m³) show timber MOR on the order of 80–100 MPa and produce CLT MOR ~35–45 MPa, with panel MOE ~10–13 GPa. Jabon (400–450 kg/m³) despite lower density achieves panel MOR ~35–40 MPa, thanks to efficient utilization of its moderate wood strength (~50–60 MPa) in a layered form. Rubberwood and coconut (outer wood) (each ~600–800 kg/m³) fall in the middle, with CLT MOR around 25–40 MPa. Sengon and Chinese fir (very low density, ~300–400 kg/m³) show the lowest MOE (~6–8 GPa) and MOR (~15–25 MPa) among wood species. Palm wood (date or coconut palm) exhibits drastically low panel MOR (often <3 MPa)—highlighting it as an outlier. Bond-line shear strengths for most wood species range 1–2 MPa (typical for softwood CLT is ~2 MPa). Notably, bamboo and some lightweight woods (jabon, balsa) reported higher values (~2.5–3 MPa), possibly due to specific test configurations. Palm's bond-line shear (~0.5–1.5 MPa at best) is well below others, reflecting weak bonds and shear paths.

5.2 AHP RANKING AND MODEL-BASED EVALUATION OF MATERIAL PROPERTIES

In this study, the application of AHP aimed to select suitable timber species for CLT production in Asia, using specific criteria based on timber properties: density, timber modulus of elasticity (MOE), and timber bending strength. The expert-defined priority weights for these criteria, derived from the AHP calculations, were identified as density (10%), timber MOE (30%), and timber bending strength (60%), see Fig. 1.

The resulting composite scores and ranking indicated that Bamboo (0.351) exhibited the most suitable combination of these properties, followed by Rubberwood (0.245), Chinese fir (0.218), and Palm Wood (0.186). This ranking underscores Bamboo's superior mechanical attributes, primarily driven by its exceptional bending strength, making it the preferred candidate among the considered alternatives.

The obtained outcomes confirm the validity of using timber bending strength as the most critical indicator for predicting the structural performance of CLT, complemented by the modulus of elasticity and density to refine the prediction. The established criteria weights enable a simplified yet robust method for assessing potential CLT species without conducting extensive CLT fabrication and testing.

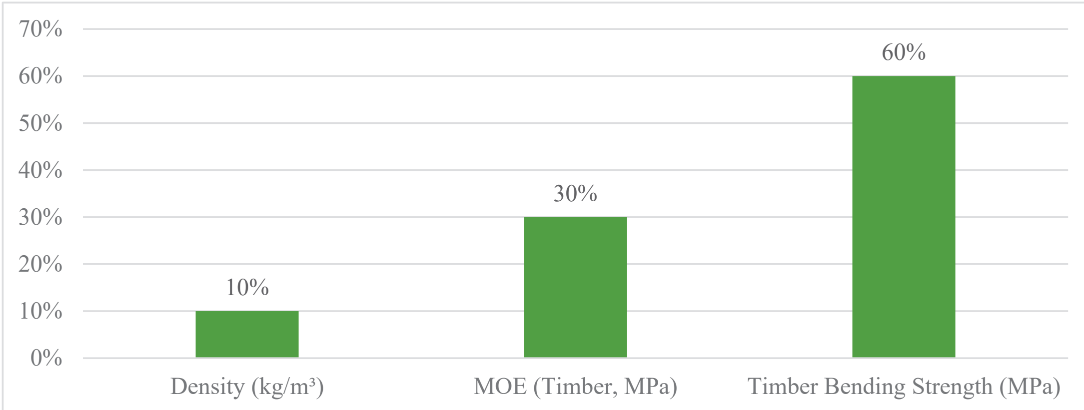

Figure 1. Priority weights for timber property criteria established by AHP methodology

6 – CONCLUSION

This research identifies optimal fast-growing Asian species and bonding parameters for CLT production:

- Bamboo, acacia, eucalyptus, and jabon exhibited superior structural-grade performances.

- PUR and PRF adhesives offered reliable bonding for tropical hardwoods; bamboo required higher pressures or MUF/PVA adhesives.

- Palm panels showed inadequate structural performance due to poor bonding capability.

- AHP rankings strongly correlated timber properties with final CLT performance, validating the predictive capability of a simpler timber-level property model with criteria weights: density (10%), MOE (30%), bending strength (60%).

These findings enable efficient preliminary material screening, reducing dependence on extensive prototype fabrication.

7 – REFERENCES

[1] S. Srivaro, H. Lim, M. Li, Z. Pasztory, "Properties of Mixed-Species/Density Cross Laminated Timber made of Rubberwood and Coconut Wood." Structures, vol. 40, pp. 237–246, 2022.

[2] L. Corpataux, S. Okuda, H.W. Kua, "Panel and plate properties of Cross-Laminated Timber (CLT) with tropical fast-growing timber species in compliance with Eurocode 5." Construction and Building Materials, vol. 258, 2020, p. 119580.

[3] S. Okuda, L. Corpataux, S. Muthukrishnan, K.H. Wei, "Cross-laminated timber with renewable and fast-growing tropical species in South East Asia." in Proc. World Conference on Timber Engineering (WCTE), Seoul, 2018.

[4] K.S. Sikora, D.O. McPolin, A.M. Harte, "Shear Strength and Durability Testing of Adhesive Bonds in Cross-Laminated Timber." The Journal of Adhesion, vol. 92, no. 8, pp. 758–777, 2016.

[5] W.Q. Xing, J.L. Hao, K.S. Sikora, "Shear Performance of Adhesive Bonding of Cross-Laminated Bamboo." Journal of Materials in Civil Engineering, vol. 31, no. 9, 2019.

[6] M. Almarri, K.S. Sikora, "Shear Strength Testing of Adhesive Bonds in Cross-Laminated Palm." In Proc. 12th Int. Conf. on Advanced Materials and Engineering Materials (ICAMEM 2023), Springer, pp. 781–789, 2024.

[7] N. Mohd Yusof, R. James, H. Choo, S.H. Lee et al., "Mechanical and physical properties of Cross-Laminated Timber made from Acacia mangium wood as function of adhesive types." Journal of Wood Science, vol. 65, no. 1, Art. 11, 2019.

[8] C. Ó Ceallaigh, K. Sikora, D. McPolin, A. Harte, "Effects of thickness of cross-laminated timber panels made from Irish Sitka spruce on mechanical performance in bending and shear." Construction and Building Materials, vol. 116, pp. 141–150, 2016.

[9] S.Y. Al Gharbi, K.S. Sikora, "Effect of Compression and Inter-Laminar Angle on the Strength of Palm Adhesive Bonds." Proc. NTCE 2023 – New Trends in Civil Engineering, 2023.

[10] M.Z. Ahmed, K.S. Sikora, "Mechanical Properties of Cross-Laminated Panels Made from Date Palm Leaves." Drewno, vol. 67, no. 213, 2024.

[11] A. Nicał, K. Sikora, "Application of AHP multicriteria assessment method for selection of wood in sustainable construction." Operational Research in

https://doi.org/10.52202/080513-0144

Engineering Sciences: Theory and Applications, vol. 5, no. 1, pp. 107–120, 2022.

[12] H. Anysz, A. Nicał, Ž. Stević, M. Grzegorzewski, K. Sikora, “Pareto Optimal Decisions in Multi-Criteria Decision Making Explained with Construction Cost Cases.” Symmetry, vol. 13, no. 1, p. 46, 2021.

[13] T.L. Saaty, “Multicriteria Decision Making: The Analytic Hierarchy Process.” McGraw-Hill, New York 1980.

[14] T.L. Saaty, “Decision making with the Analytic Hierarchy Process.” International Journal of Services Sciences, vol. 1, pp. 83–98, 2008.

[15] W.Q. Xing, J.L. Hao, I. Galobardes, S.B. Wei, Z.T. Chen, K.S. Sikora. “Engineered bamboo’s further application: An empirical study in China.” In MATEC Web of Conferences, EDP Sciences, vol. 206, 2018.

[16] H. AlQahtani, S. Amir, K. Jaafar, Y. Salah, K.S. Sikora. "Effect of Compression and Inter-Laminar Angle on the Strength of Palm Adhesive Bonds." In International Conference on Civil Engineering and Materials Science, pp. 93-102. Singapore: Springer Nature Singapore, 2024.

[17] S. Srivaro, Z. Pasztory, H.A. Le Duong, H. Lim, “Physical, mechanical and thermal properties of cross laminated timber made with coconut wood.” European Journal of Wood and Wood Products, vol. 79, pp. 1519–1529, 2021.

[18] M. Derikvand, H. Jiao, N. Kotlarewski, M. Lee, A. Chan, G. Nolan. “Bending performance of nail-laminated timber constructed of fast-grown plantation eucalypt.” European Journal of Wood and Wood Products, vol 77, pp. 421-437, 2019.

[19] H. Pangh, H.Z. Hosseinabadi, N. Kotlarewski, P. Moradpour, M. Lee, G. Nolan. “Flexural performance of cross-laminated timber constructed from fibre-managed plantation eucalyptus.” Construction and Building Materials, vol. 208, pp. 535-542, 2019.

[20] Y. Liao, D. Tu, J. Zhou, H. Zhou, H. Yun, J. Gu, C. Hu. ”Feasibility of manufacturing cross-laminated timber using fast-grown small diameter eucalyptus lumbers.” Construction and Building Materials, vol. 132, pp. 508-515, 2017.

[21] A. Yusoh, M.K.A. Uyup,P.M. Tahir, S.H. Lee, O.C. Beng. “Mechanical performance and failure characteristics of cross laminated timber (CLT) manufactured from tropical hardwoods species.” Physical Sciences Reviews, vol. 9, 2022.

[22] T. Yin, L. He, Q. Huang, Y. Gong, Z. Wang, M. Gong. “Effect of lamination grade on bending and shear properties of CLT made from fast-growing Chinese fir.” Industrial Crops and Products, vol. 207, pp. 117741 2024.

[23] C. Choi, E. Kojima, K.J. Kim, M. Yamasaki, Y. Sasaki, S.G. Kang. “Analysis of mechanical properties of cross-laminated timber (CLT) with plywood using Korean larch.” BioResources, vol. 13, pp. 2715-2726, 2018.

[24] R. Wang, J.J. Shi, M.K. Xia, Z. Li, “Rolling shear performance shear performance of cross-laminated bamboo-balsa timber panels.” Construction and Building Materials, vol. 299, p. 123973, 2021.

[25] N.M. Bhkari, L. W Chen, A Azmi, M.S. Nordin, N.W. Yam, Z. Ahmad, L.S. Hua. “Bending, compression and bonding performance of cross-laminated timber (CLT) made from Malaysian fast-growing timbers.” J. Renew. Mater., vol. 10, pp. 2851-2869, 2022.

[26] F. Muñoz, C. Tenorio, R. Moya, A. Navarro-Mora. “CLT fabricated with Gmelina arborea and Tectona grandis wood from fast-growth forest plantations: Physical and mechanical properties.” Journal of Renewable Materials, vol. 10, 2022.

[27] Y. Yau, A. Ocholi, J.M. Kaura, A. Lawan, T.A. Sulaiman. “Evaluation of shear strength and durability of adhesive bond in cross-laminated timber (CLT) panels made from Nigerian Gmelina arborea timber.” Case Studies in Construction Materials, 2024 .