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Thermal Transmittance, Dimensional Stability, and Mechanical Properties of a Three-Layer Laminated Wood Made from Fir and Meranti and Its Potential Application for Wood-Frame Windows

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Abstract: The aim of this paper was to investigate the physical (thermal transmittance and dimensional stability) and mechanical properties of two types of three layer laminated wood made from fir and meranti; fir in surface layers and meranti in core (FMF) and vice versa (MFM) and to examine its potential application for wood-frame windows. An additional objective was to compare the properties of the laminated wood with those of solid wood, namely meranti and fir. Both types of laminated wood had by far substantial lower bending properties than solid wood. MFM laminated wood performed better than the FMF as far as the physical and mechanical properties are concerned. Water absorption and thickness swelling of MFM laminated wood were substantially lower than those of the FMF type, and all the differences were statistically significant. Longitudinal width swelling, and bending properties of MFM laminated wood were higher than those of FMF but these differences were not statistically significant. The thermal transmittance (rate of the heat transferred) of the FMF window is 13.3% better (less) compared to the MFM window. The main reason for this is believed to be the lower overall density of the FMF window, which also makes it more competitive as a result of the reduced manufacturing cost since fir is less expensive compared tomeranti. It was concluded that wood-frame windows can be successfully made from these types of laminated wood, employing therefore easily renewable materials, with low environmental impact, recyclable and manageable in the medium term.

Keywords: laminated wood; meranti; fir; physical properties; mechanical properties; wood-frame windows; thermal transmittance

1. Introduction

An important distinction between timber and other structural materials is that timber is quite difficult to meet performance requirements, whereas man-made products like steel and concrete can be easily modified through the manufacturing process for a specified use. In addition, the currently growing demand for engineered wood products is largely attributable to their outstanding ecological performance. The substitution of materials having a larger ecological footprint, such as steel and concrete, by structural engineered wood products like laminated wood has proven to be effective in minimizing the environmental impacts of the building sector [1]. Furthermore, laminated wood is a material of a great aesthetic value, with various applications in the field of building components, such as doors and windows, and in the field of timber structures of big and small spans [2,3].

Nearly any species or mixed-species combination can be used to produce laminated wood provided its physical and mechanical properties are suitable and the timbers can be glued together. According to Moody and Hernandez [4], species and mixed-species combination commonly used for glued-laminated timber in the United States include southern pine (*Pinus* spp.), Douglas fir (*Pseudotsugamenziesii*), larch (*Larixoccidentalis*), hemlock (*Tsugaheterophylla*), and spruce (*Picea* spp.). Red maple (*Acer* spp.) species was also used by Janowiak et al. [5] to study the performance of glulam beam made from two distinct timber resources, namely sawn logs and lower-grade, smaller-dimension timber. Komariah et al. [6] developed glulam made from sengon, manii, and mangium, with either the same wood species being used for all layers or mangium being used for the face and back layers, with a core layer of manii or sengon. The physical and mechanical properties of the glulam did not show any significant difference from that of solid wood of the same species. Such samples successfully fulfilled the JAS 234 (Japanese Agricultural Standard 2003) standard [7]. Similar results were reported by Hayashi and Miyatake [8] for structural laminated timber made from Japanese cedar.

The tremendous diversity of tropical hardwoods available for structural applications significantly compounds the complexity of matching a particular species of timber with specific performance requirements. The number of merchantable species of timber available has been reported at 650 for Malaysia [9] and 2500 in the Amazon [10]. There is a tendency in most regions to use clear material from a few species for which considerable experience is available on long-term structural performance. Corigliano et al. [11] performed theoretical and experimental analyses of Iroko wood laminates. The experimental results demonstrated that the presence of scarf joints only affected the strength of the glued laminate while the stiffness properties remained the same. Various bamboo species have also been used for the manufacture of laminated wood [12].

Meranti is a common name applied commercially to four groups of species from the genus *Shorea*. The four groups of meranti are separated on the basis of heartwood color and weight. About 70 species of *Shorea* belong to the light and dark red meranti groups, 22 species to the white meranti group, and 33 species to the yellow meranti group. *Shoreapauciflora*, a dark red meranti, is very commonly used in southeast Asia, and there is an abundance of variety between the difference species.Few studies have been published regarding the application of meranti as a raw material for laminated wood manufacture. Hartono and Sucipto [13] made three layer laminated wood from oil palm trunk in the core, a low quality raw material, and applied high density woods in the surface layers, namely sengon and meranti. They reported strong relationship between density and bending properties and they concluded that the best combination was that of oil palm trunk in the core layer and meranti in the surface layers. Modulus of rupture (MOR) and modulus of elasticity (MOE) values for laminated wood made purely from oil palm trunk was 168.79 and 30,115 (Kg/cm^2), whereas the ones made from oil palm trunk in the core layer and meranti in the surface layers was 438.29 and 100,454 respectively. Puluhulawa et al. [14] manufactured three-layer laminated wood using a light wood in the core (mahang) and meranti in the surface layers. They reported that the laminated wood had by far substantial lower bending properties than meranti solid wood. Ong [15] investigated the performance of glue-laminated beams from Malaysian dark red meranti timber. Phenol resorcinol formaldehyde, commonly used in structural glulam production, was used in the fabrication of finger joints and laminations of the glulam beams. Overall, it was found that dark red merantifinger joints exhibited better bending strength than spruce finger joints which represented softwood used in European glulam. Wood density and end pressure were shown to affect the strength properties of the finger joints.

It was mentioned earlier that physical and mechanical properties of the low-quality timber can be improved by processing it into glued laminated wood or to be combined with tropical woods to obtain value added wood products. Consequently, the aim of this paper was two-fold:

(1) To investigate the physical (thermal transmittance and dimensional stability) and mechanical properties of two types of three layer laminated wood made from fir and meranti; fir in surface layers and meranti in core and vice versaand to examine its potential application for wood-frame windows.

(2) An additional objective was to compare the properties of the laminated wood with those of solid wood, namely meranti and fir.

2. Materials and Methods

2.1. Specimen Preparation

Fir (*Abies alba* Mill) and meranti (*Shoreapauciflora*) boards were supplied by a local plant (Halucom, Karditsa, Greece); they were kept in the wood workshop for five months before being cut to size, 360 mm in length, 25 mm in width (plain sawn), and 20 mm in thickness. Specimens were free from any fungal or insect attack, checks or cracks, and knots. The density of fir and meranti specimens was measured to be 0.43 and 0.47 $Kg \cdot m^{-3}$, respectively, at moisture contents of 11.56% and 10.13% respectively. Physical and mechanical properties—namely density, water absorption after 24, 48 and 72 h immersion in water, and swelling (both longitudinal, width and thickness) after 24, 48 and 72 h, modulus of rupture (MOR), and modulus of elasticity (MOE)—were determined in accordance with ASTM D0143-94 [16]. Tests were carried out at room conditions (25 ± 3 °C; 35% ± 3% relative humidity).

2.2. Manufacture of Laminated Wood

Fir and meranti specimens, $20 \times 25 \times 360$ mm^3 (thickness × width × length), were conditioned at 20 °C temperature and 65% relative humidity until the weight of the wood was stabilized. Two types of three-layer laminated wood produced from fir and meranti, namely fir in surface layers and meranti in core (FMF), and vice versa (MFM), as depicted in Figure 1. Laminated wood made from meranti in both core and surface layers was not manufactured due to the high cost involved. On the other hand, laminated wood made from fir in both core and surface layers was not manufactured, since it was expected to show very low dimensional stability. A two-component polyvinyl acetate wood adhesive for outdoor use was applied, with the following properties. viscosity: 11,000−14,000 mPas (Brookfield RVT, 20 rpm, at 23 °C), pH value: approx. 4−5.5, at 20 °C, density: ca. 1.13 g/cm^3 at 20 °C, mixing rate adhesive/hardener (by weight) 15:1, mixture pH value: approximately 3.2.Polyvinyl acetate (PVAc) based glue was applied by brush on one side of the joints. PVAc was selected due its low cost and its easy applicability. Once glued, they were kept together for 60 s, using a manually operated press. The wood samples were subjected to a constant hydraulic pressure of 5 bar (per surface) and an ambient temperature of 20 °C for 12 h. The laminated wood specimens were conditioned and cut to the final dimensions of $20 \times 75 \times 360$ mm^3 (thickness × width × length). Bending strength (modulus of rupture; MOR and modulus of elasticity; MOE) of the specimens was determined according to the procedures detailed in the EN 385:2001 [17]. Also, physical properties, namely density, water absorption after 24, 48, and 72 h and swelling (both longitudinal, width, and thickness) after 24, 48, and 72 h immersion in water, were determinedaccording to the procedures detailed in the EN 385:2001.

(**a**) (**b**)

Figure 1. Types of laminated wood; fir in surface layers and meranti in core (FMF—**a**) and meranti in surface layers and fir in core (MFM—**b**).

2.3. Thermal Transmittance Determination

Commercial wood frame windows manufactured with the two types of the investigated laminated wood, namely fir in surface layers and meranti in core (FMF) and vice versa (MFM), were supplied from a local plant and their thermal transmittance is determined. The thermal transmittance of solid wood, fir and meranti, is also determined.

The thermal transmittance, also referred as U-value, is the heat flow rate divided by the area and temperature difference in the surroundings of both sides of a system at a steady state [18] and is a concept employed to describe the insulation properties for the building materials, in our case for windows. The inside pane of a double-glazed window captivates heat from the inner side and transmits it through conduction and convection to the cooler pane (outside of the window) [19]. Heat conduction in windows is ruled by the material of the frame. Wood has a rather high thermal insulation properties (average thermal conductivity λw = 0.13 W/mK) [20–24]. This, in a wood window frame, results in less heat loss compared to the window frames constructed from other materials which have greater thermal conductivity values.

A heat flux measuring device (Testo North America, West Chester, USA) (HFM-Testo 635-2/ accuracy: ±0.2 °C/operating temperature: −20 to +50 °C with a wireless humidity/temperature probe) has been used to calculate the window's thermal transmittance. This apparatus measures the specific heat flow (q) and the air temperatures for the two sides (T_w'warm' and T_c'cold') of the window with the assistance of a wireless temperature probe [25]. Having reading from these three parameters, the U-value is being calculated automatically using the Equation (1)

$$U = \frac{q}{(T_w - T_c)} \left(\mathrm{W/m^2{\cdot}K}\right) \quad (1)$$

The external dimensions of the window frame for the two sample windows were 1000×1000 mm^2 with a frame height of 100 mm and frame thickness of 68 mm. The double glazed window had the following setup: "4-12-4". This is translated into 4 mm glass thickness and 12 mm gap between the two glass panes. Double glazed windows are principally the combination of double glass window panes separated by an air or other inert gas filled space in order to reduce heat loss through a part of the building envelope.

The thermal transmittance (U-value) readings for the two windows were undertaken according to the ISO 9869-1:2014 [18] and to the BS EN ISO 10077-2 [26]. The required parameters to calculate the thermal transmittance of a window (U_w) are the following: The value of the window's frame (U_f), the value of the double-glazed pane (U_g) and also the length (area) of the window frame and the glass.

At both windows, the same thermal insulating glass was used with a thermal transmittance value given by the manufacturer: U_g = 1.8 W/m^2·K.

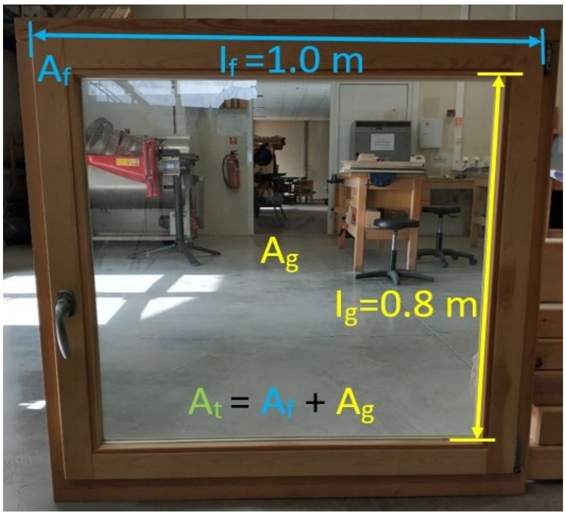
The calculation method of the window's thermal transmittance is based on the following Equation (2) explained with details in Figure 2:

$$U_w = \frac{\Sigma A_g U_g + \Sigma A_f U_f + \Sigma l_g \Psi_g}{\Sigma A_g + \Sigma A_f} \left(\mathrm{W/m^2 \cdot K}\right) \quad (2)$$

where:

ΣA_g: summation of the window's glass pane area (m^2)
ΣA_f: summation of the window's frame area (m^2)
U_g: thermal transmittance of the glass pane (W/m^{2}K)
U_f: thermal transmittance of the window's frame (W/m^{2}K)
Σl_g: summation of the window's glass pane length—perimeter (m)
Ψ_g: linear heat transfer coefficient of the glass pane (W/mK)
Incorporating the above data on to the Equation (2),we can derive:

$$U_w = \frac{\Sigma A_g U_g + \Sigma A_f U_f + \Sigma l_g \Psi_g}{\Sigma A_g + \Sigma A_f} = \frac{0.64 \times 1.8 + 0.36 \times U_f + 3.2 \times 0.08}{0.64 + 0.36} \left(\mathrm{W/m^2 \cdot K}\right) \quad (3)$$

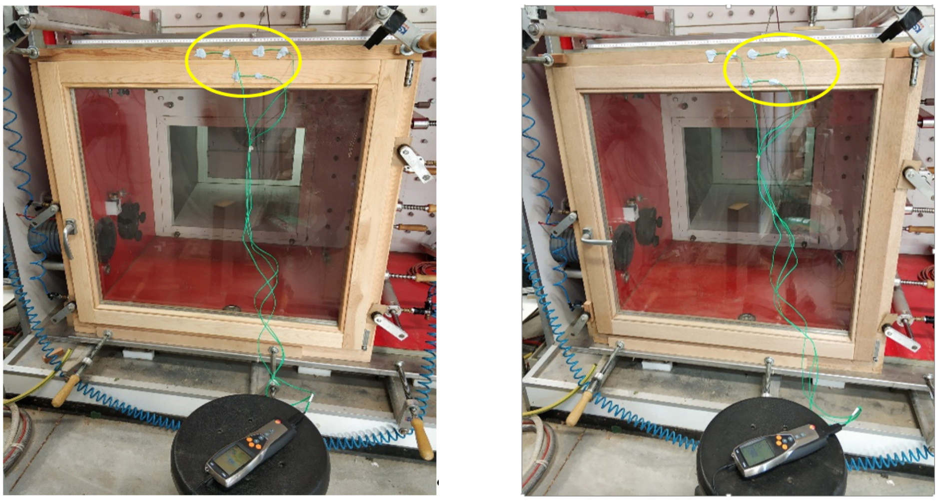


U_g = 1.8 W/(m^2·K) (manufacturer)
U_f = window frame thermal transmittance
A_g = 0.8 × 0.8m= 0.64 m^2
A_f = A_t − A_g = 1^2 − 0.64 = 0.36 m^2(A_t: window's total area)
Ψ_g = 0.08 (for a timber frame with a double glazed window with air between the two panes)

Figure 2. The tested wood-frame window.

The calculation of the window frame's thermal transmittance (U_f) was based on the following setup. This was achieved with the use of window testing apparatus where the 'cold' side temperature is being adjusted electronically by a wireless probe. The view of the tested windows mounted into the 'window tester' is given in Figure 3. The temperature of the 'warm' side, is also adjustable electronically by a digital thermostat.

Before starting the experiments for the window frame's thermal transmittance (U_f), the 'cold' and 'warm' side temperatures were adjusted at 6 °C (±1 °C) and 15 °C (±1 °C) respectively and remained within these boundaries for 76 h. The three HFM's thermocouples were positioned in a 0.10 m triangle setup to capture the heat flow connected to the HFM (Figure 3). During this period, the U-values for each window were recorded by the HFM device.



FMF MFM

Figure 3. The HFM device with the attached thermocouples (green-cable edges at the yellow circle) taking reading for a 72 h period.

2.4. Statistical Analysis

SAS software program was used to carry out statistical analysis in the present study (version 9.2; 2010). To discern significant difference among different treatments and produced panels, one-way analysis of variance was performed at 95% level of confidence. Then, Duncan's multiple range test (DMRT) was done for grouping among treatments for each property. In order to find degrees of similarities among different treatments based on all properties studied here, Hierarchical cluster analysis from SPSS/18 (2010) software (version 9.2) was used. In a cluster analysis, there is a scale bar on top; those treatments that are connected at lower scale levels (that is, lower numbers on the scale bar) by a vertical line are considered to be more similar, in comparison to those that are connected at higher scale levels. The maximum scale (number 25) indicates that treatments have practically very little in common and therefore, they are to be considered as two completely different ones [27]. In DMRT, different treatments are grouped based on only one property. However, cluster analysis can do groupings among different treatments based on more than one property. This capability provides useful information for managers who are to make decisions based on all aspects and perspectives, and to choose the most appropriate option for their production program. This type of statistical analysis can be used for all kinds of materials, including wood species, wood-based composites, papers, and even cloths [28,29]. For graphical statistics (fitted-line, contour, and surface plots), Minitab software was utilized (version 16.2.2; 2010).

3. Results

The moisture content of the FMF and MFM laminated wood was determined to be 10.36% and 10.41% respectively and these values are nearly the same with those of solid wood, as mentioned in session 2.1. The density of the FMF and MFM laminated wood was 0.44 and 0.49 $Kg{\cdot}m^{-3}$ respectively, values close to the density of fir and meranti solid wood (0.43 and 0.47 $Kg{\cdot}m^{-3}$ respectively), a fact that indicates that the density of the laminated wood was not affected by the density of the solid wood.

The physical properties of both fir and meranti wood are presented in Table 1. Water absorption and thickness swelling of meranti specimens after 24, 48, and 72 h immersion in water were substantially lower than those of the fir wood and this difference is statistically significant. Table 2 shows the bending properties of the two wood species. It was revealed that both MOR and MOE values of fir wood were higher than those of meranti wood and the difference was statistically significant.

Table 1. Physical properties of fir and meranti wood.

Wood Species	Physical Properties [a]		
	Water Absorption (%)		
	24 h	**48 h**	**72 h**
fir	39.44 (±7.75) [b] A [c]	51.02 (±9.81) A	58.84 (±10.9) A
meranti	18.05 (±0.70) B	23.08 (±0.70) B	25.84 (±0.68) B
Wood Species	Longitudinal Swelling (Axial) (%)		
	24 h	48 h	72 h
fir	0.06 (±0.01) A	0.10 (±0.09) A	0.12 (±0.09) A
meranti	−0.16 (±0.04) B	−0.11 (±0.04) B	−0.09 (±0.04) B
Wood Species	Width Swelling (Tangential) (%)		
	24 h	48 h	72 h
fir	2.03 (±0.97) A	3.08 (±0.95) A	3.3 (±1.27) A
meranti	0.31 (±0.02) B	1.41 (±0.42) B	1.87 (±0.34) B
Wood Species	Thickness Swelling (Radial) (%)		
	24 h	48 h	72 h
fir	1.79 (±0.86) A	2.46 (±0.73) A	2.8 (±0.73) A
meranti	0.67 (±0.031) B	1.67 (±0.29) B	2.26 (±0.36) B

[a] Each value is the mean of six replicates; [b] Standard deviation; [c] Letters on each column represent Duncan groupings at 95% level of confidence.

Table 2. Bending properties of fir and meranti wood.

Wood Species	Bending Properties [a]	
	MOR (N/mm²)	**MOE (N/mm²)**
fir	68.66 (±6.54) [b] A [c]	8796.73 (±1254.32) A
meranti	48.81 (±3.92) B	6771.6 (±780.16) B

[a] Each value is the mean of four replicates (determined in the radial direction of the solid wood samples); [b] Standard deviation; [c] Letters on each column represent Duncan groupings at 95% level of confidence.

Table 3 depicts the physical properties of the two types of laminated wood investigated in this study. It was revealed that those laminated specimens with fir wood on the surface layers had higher water absorption and thickness swelling values than those with meranti on the core layer. The bending properties of the two types of laminated wood are presented in Table 4. MFM laminated wood presented better bending properties than FMF. Going back to the Equation (2), the overall window thermal transmittance is as follows:

For the FMF window, as shown in Equation (4),

$$U_{w-FMF} = \frac{\Sigma A_g\ U_g\ + \Sigma A_f\ U_f\ + \Sigma l_g\ \Psi_g}{\Sigma A_g + \Sigma A_f} = \frac{0.64\times 1.8 + 0.36\times\ U_f\ + 3.2\times 0.08}{0.64+0.36} = \frac{0.64\times 1.8 + 0.36\times 0.775 + 3.2\times 0.08}{0.64+0.36} = 1.687\ \ \mathrm{W/m^2{\cdot}K} \tag{4}$$

and for MFM window, as shown in Equation (5),

$$U_{w-MFM} = \frac{\Sigma A_g U_g + \Sigma A_f U_f + \Sigma l_g \Psi_g}{\Sigma A_g + \Sigma A_f} = \frac{0.64\times 1.8 + 0.36\times U_f + 3.2\times 0.08}{0.64+0.36} = \frac{0.64\times 1.8 + 0.36\times 1.494 + 3.2\times 0.08}{0.64+0.36} = 1.946\ \ \mathrm{W/m^2{\cdot}K} \tag{5}$$

Table 3. Physical properties of the two types of laminated wood.

Laminated Wood	**Physical Properties [a]**		
	Water Absorption (%)		
	24 h	**48 h**	**72 h**
MFM	20.51 (±1.48) [b] A [c]	25.4 (±1.53) A	27.60 (±1.34) A
FMF	26.21 (±0.61) B	32.34 (±0.64) B	34.93 (±0.51) B
Laminated wood	Longitudinal Swelling (%)		
	24 h	48 h	72 h
MFM	−0.04 (±0.005) A	−0.02 (±0.004) A	0.00 (±0.004) A
FMF	0.00 (±0.003) A	0.01 (±0.003) A	0.03 (±0.004) A
Laminated wood	Width Swelling (%)		
	24 h	48 h	72 h
MFM	1.42 (±0.48) A	2.07 (±0.35) A	2.62 (±0.31) A
FMF	1.85 (±0.21) A	2.67 (±0.26) A	2.95 (±0.28) A
Laminated wood	Thickness Swelling (%)		
	24 h	48 h	72 h
MFM	0.06 (±0.063) A	0.86 (±0.090) A	2.43 (±0.75) A
FMF	2.61 (±1.14) B	4.79 (±1.04) B	5.41 (±0.83) B

[a] Each value is the mean of six replicates (The directions of the solid wood samples used for the manufacturing of the laminated wood were not predefined); [b] Standard deviation; [c] Letters on each column represent Duncan groupings at 95% level of confidence.

Table 4. Bending properties of the two types of laminated wood.

Laminated Wood	**Bending Properties [a]**	
	MOR (N/mm^2)	**MOE (N/mm^2)**
MFM	14.47 (±1.56) [b] A [c]	5659.51 (±697.41) A
FMF	13.81 (±1.51) A	4571.99 (±798.47) A

[a] Each value is the mean of four replicates. The directions of the solid wood samples used for the manufacturing of the laminated wood were not predefined; [b] Standard deviation; [c] Letters on each column represent Duncan groupings at 95% level of confidence.

In Table 5, the two window's thermal transmittance values are displayed.

Table 5. Thermal transmittance of the windows (U_W).

Window Type	**Window's Thermal Transmittance U_W (W/m^2·K)**
FMF	1.687
MFM	1.946

Contour plots of the four treatments based on water absorption after 24 h immersion in water and other physical and mechanical properties demonstrated a general positive relationship between physical and mechanical properties (Figure 4A,B). Based on water absorption and thickness swelling, as well as MOR and MOE values, reported in Tables 1 and 2, it was clear that fir wood had higher mechanical properties in comparison to meranti, though meranti had a higher density. Moreover, it was fir wood that demonstrated higher thickness swelling and water absorption. Thickness swelling in solid wood species occurs in woody mass. Moreover, mechanical properties are also positively related to woody mass in each solid wood species. Although the above mentioned contour plots demonstrated a positive relationship, some inconsistency was also obvious in the graphs.

The inconsistency indicated that there were other factors affecting the outcome of the relationship between physical and mechanical properties. Factors like vessel properties (vessel diameter, frequency, and specific area), type and size of pit openings, and extractive contents are just a few examples of the factors that significantly affect permeability in solid wood species [30–32], which in turn determine thickness swelling and water absorption behaviors. Moreover, the way microfibrils are oriented in wood cell wall (primary and secondary walls) would also significantly affect mechanical properties, regardless of the woody mass. The above mentioned inconsistency was primarily attributed to the interactions of these factors that influence physical and mechanical properties. The inconsistency was also partially attributed to an interference caused by addition of resin in the laminated wood. The effect of the addition was also apparent in the thermal transmittance of boards, resulting in a significant increase in the thermal coefficient values of the laminated wood in comparison to the solid wood specimens (Table 5) [33,34].

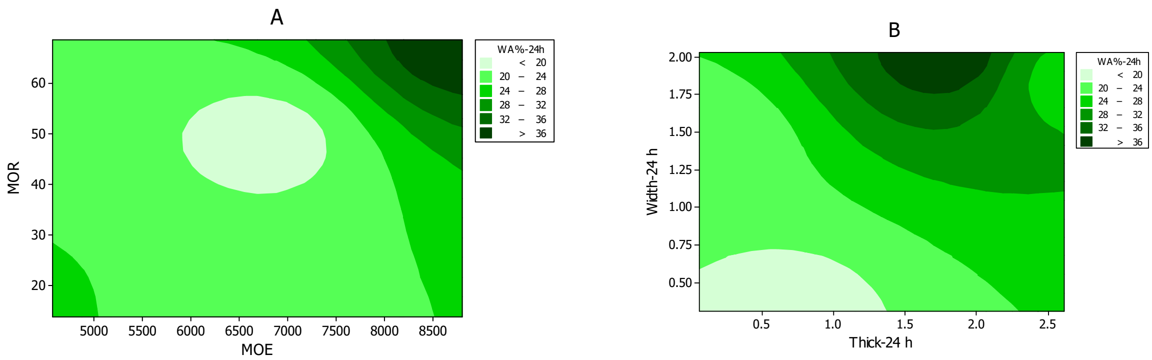


Figure 4. Contour plots between physical and mechanical properties of three-layer laminated wood made from fir and meranti wood (**A**: MOR = modulus of rupture; MOE = modulus of elasticity; and **B**: WA = water absorption; Width and Thick-24 h = width and thickness swelling after 24 h immersion in water).

Cluster analysis was carried out for four treatments, and based on all the physical and mechanical properties studied here. The properties included water absorption, longitudinal, width, and thickness swelling, as well as modulus of rupture, modulus of elasticity, and thermal transmittance coefficient. The four treatments consisted of the two laminated wood (MFM and FMF), along with the values of the two solid wood species of "fir" and "meranti". This statistical analysis revealed that two treatments of meranti solid wood and MFM laminated wood were connected by a vertical line at about number "one" on the scale bar (on top of the graph) (Figure 5). This indicates that these two treatments are very similar based on all the properties studied here. Similar observations were reported by Hartono and Sucipto [13] who made three layer laminated wood from oil palm trunk in the core, a low quality raw material, and applied high density woods in the surface layers, namely sengon and meranti. Based on the similarity demonstrated between meranti solid wood and MFM laminated wood, it can be concluded that the potential applications of this engineered laminated wood (MFM) can be considered nearly the same as can be expected from the physical and mechanical qualities meranti solid wood. Using this engineered laminated wood, forests and woody resources can more efficiently be preserved and more practically be used for different applications. However, the cluster analysis illustrated that "fir" was connected at scale No. 25 with the other three treatments. This indicated that fir, as asolid wood, reacted quite differently, and it was to be considered as a material with completely different properties. Table 2 demonstrated that the mechanical properties of fir solid wood were significantly higher than those of meranti solid wood. The reason for the substantial decrease in the mechanical properties of FMF laminated wood can be elaborated from different perspectives. It was previously reported that shear strength and failure patterns in glue line were significantly dependent on the mechanical properties of the wood [35,36]. The cited authors explained that failure occurred in the glue line when shear strength of the wood used in the experiment was higher than that of the glue itself. However, if the mechanical properties of the wood were low, or thermal modification had made the woody parts weaker, failures occurred in the wooden parts [32,36,37]. In the present study, meranti wood had significantly lower mechanical properties in comparison to fir solid wood (Table 2). Therefore, MFM laminated wood were expected to be very similar to those of meranti solid wood, because fir was used in the core; that is, the neutral zone which is less important. However, fir solid wood had significantly higher mechanical properties; therefore, in FMF laminated wood, the failure occurred in the glue line and before the two fir wood layers on the top and bottom surfaces failed, it was the glue line that failed, resulting in a substantial decrease in the overall mechanical properties. The eventual outcome of the above mentioned facts resulted in close clustering of meranti solid wood with MFM laminated wood, as well as remote clustering of fir solid wood with FMF laminated wood. It was concluded that laminated wood with fir on the surface layers are not recommended with regard to their substantial decrease in mechanical properties, and significant increase in physical properties, when compared with values of fir solid wood specimens.

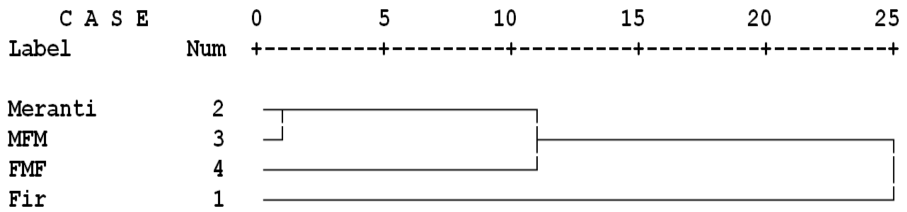


Figure 5. Cluster analysis of the four treatments based on the physical and mechanical properties.

4. Discussion

From the data presented in Table 3, it was revealed that those laminated specimens with fir wood on the surface layers had higher water absorption and thickness swelling values than those with meranti on the core layer. This was quite in agreement with the values of fir and meranti as solid wood specimens (Table 2). That is, meranti showed preferably lower water absorption and thickness swelling values in comparison to fir, both in form of solid wood and in form of laminated wood when the surface layers were made of fir wood. MOR measurement, as a vitally important mechanical property, demonstrated higher values for MFM boards in comparison to FMF ones.

Closer inspection of the data presented in Tables 1 and 3, reveals that the physical properties of the laminated wood made from meranti in surface layers and fir in core (MFM) were nearly the same with those of meranti solid wood. From this observation, it can be concluded that the presence of fir in the core did not affected the physical properties of the laminated wood. On the other hand, the laminated wood made from fir in surface layers and meranti in core (FMF), showed substantially lower values compared to meranti solid wood. It is of interest to mention the high thickness swelling values of FMF laminated wood as depicted in Table 3, which can be attributed to the slight delamination occurred; this was more pronounced in FMF laminated wood.

By referring to the data presented in Tables 2 and 4, it is clear that both types of laminated wood had substantially lower bending properties than solid wood. This in line with the observations made by Puluhulawa et al. [14] who manufactured three layer laminated wood using a light wood in the core (mahang) and meranti in the surface layers.It is interesting to notice that the fir solid wood has MOR values nearly five times more than MFM laminated wood, and the MOE value of MFM laminated wood is nearly 55% lower that the MOE of fir solid wood. These low values in bending properties of both types of laminated wood produced in this study can be attributed to the delamination occurred, and as expected MOR was affected to a greater extent than MOE. A decrease of about 33% in bending properties was also reported by Corigliano et al. [11] for Iroko wood laminates. Papadopoulos reported that the MOR and MOE values of finger jointed beech wood are

76.4% and 10% lower that the corresponding values of beech solid wood [38]. Similar observations were also reported in mixed glued laminated timber of poplar and Eucalyptus grandis clones [39]. On the other hand, Mohamad et al. [40] evaluated the bending strength behavior of laminated wood manufactured using two Malaysian hardwood timber species from different strength grouping, namely keruing (*Dipterocarpus* spp.) and resak (*Vatica* spp. and *Cotylelibium* spp.). They concluded that the strength grouping does not correlate well with the strength of timbers in structural size. They further stated that bending strength values of glulam was mainly affected by the ability of timber to bond well between laminates in relation of the density of the timber. Hayashi and Miyatake [8] reported that bending strength of three Japanese wood species—namely sugi, todomatsu and ezomatsu composite glulam—is decreased by the use of other species of laminae having high MOE for outer layers and this is in line with the observations made in this study. The use of fir, a wood species that has higher MOE values than meranti as depicted in Table 2, in the surface layers, affected the bending properties of the laminated wood since the bending properties of FMF were found to be lower than those of MFM.

Overall, MFM laminated wood presented better bending properties than FMF, as depicted in Table 4. This can be explained by the fact that the core layer experiences lower compressive and tensile stresses compared to the face and back layers. This wood species combination was effective because wood with the lower density can safely be used as a core layer [41].

A clear limitation of this study is the fact that bondability tests were not carried out. It is well known that the bending properties of laminated wood were strongly affected by the ability of wood to bond well between laminates and by the combination of two different wood species, especially without any type of joint. Since the laminating effect in laminated wood stems from the fact that laminations are bonded, the integrity of the cross-section is a crucial factor in the overall product performance [42,43]. As it is mentioned by Frihart et al. [44] and Selbo [45], the resistance to moisture and the bonding quality remains issues that are usually neglected in studies where tropical woods are used for manufacturing of laminated wood. It is reported that the small lumens and the thick cell walls of tropical woods usually lead to a limited penetration of the adhesive used which in turn results inweakened bondlines [44,45]. According to Konnerth et al. [46] and Knorz et al. [47], the bond strength of several European and tropical wood may greatly vary depending on the adhesive system and wood species. Therefore, and taking into consideration the inherent difficulties of bonding tropical woods, the adhesive system and the bondline strength of a given species should be carefully assessed in order to confirm their potential use as a engineered wood product such as laminated wood, especially if there are for structural applications. It has to be mentioned at this stage, that in Canada no laminated wood products made from hardwood and tropical wood species, designed for structural applications, are available on the market. The CSAO122 [48] standard, governing the manufacturing and quality control testing of structural glued-laminated timber, does not include any provision regarding the use of hardwood and tropical wood species.

Table 5, displays the two window's thermal transmittance values. From this it can be seen that the FMF window shows slightly better (lower) thermal transmittance value than the MFM window. This can be attributed to the slightly lower density of the fir wood compared to meranti wood (0.43 and 0.47 $\text{Kg}\cdot\text{m}^{-3}$ respectively), to its lighter color and to the presence of resin canals in the fir wood [49,50]. It is known that thermal conductivity of a material depends on its temperature, moisture and density. Generally, light materials are better insulators than heavy materials because light materials often contain enclosures. When it comes to insulation, the lower the thermal conductivity the better insulation capacity; if a material conducts heat well, a lot of heat will be lost through that material. This difference is translated into a 13.3% better thermal behavior of the FMF window. A smaller U-value means smaller heat transfer rate, so less energy loss.

It was concluded that based on the experiments carried out in the present study, laminated wood with meranti wood on the surface layers are recommended for the industry. Wood-frame windows can be successfully made from laminated wood with meranti wood on the surface layers, therefore employing easily renewable materials, with low environmental impact, that are recyclable and manageable in the medium term.

Future work may involve bondability tests, since it is well known that the bending properties of laminated wood are strongly affected by the ability of wood to bond well between laminates and by the combination of two different wood species, especially without any type of joint. In addition, the application of other adhesive systems may be an avenue for exploitation.

5. Conclusions

The aim of this paper was to investigate the physical (thermal transmittance and dimensional stability) and mechanical properties of two types of three layer laminated wood made from fir and meranti; fir in surface layers and meranti in core (FMF) and vice versa (MFM) and to examine its potential application for wood-frame windows.MFM laminated wood performed better than the FMF as far as the physical and mechanical properties are concerned. The thermal transmittance (rate of the heat transferred) of the FMF window is 13.3% better (lower) compared to the MFM window. The main reason for this is believed to be the lower overall density of the FMF window, which also makes it more competitive as a result of the reduced manufacturing cost since fir is less expensive compared to meranti. It was concluded that wood-frame windows can be successfully made from these types of laminated wood.

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