Thermal Insulation Properties of Cross-laminated Timber Panels with Different Geometric Interlayers in Various Temperature Environments

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Three-layer cross-laminated timber (CLT) panels were produced using Scots pine (*Pinus sylvestris* L.) for the outer layers and poplar (*Populus*) for the middle layer. Circular, rectangular, and trapezoidal geometric corrugates were applied to the middle layer; the aim was to determine the air-dry density, moisture content, thermal conductivity (*λ*), and thermal transmittance (*U*) values of the resulting panels under three different climatic conditions. The moisture content of the geometric corrugated CLT panels was higher than that of the control group. In contrast, the air-dry density values were approximately 15% lower than those of the control group. The lowest value of the thermal conductivity coefficient was obtained for the circular- corrugated panel at an average of 0.099 W/m·K, while this value was measured at 0.108 W/m·K for the control group. Similarly, the thermal transmittance coefficient also showed the lowest value, 2.026 W/m²·K, in the circular- corrugated panel. Both the corrugate geometry and ambient temperature had statistically significant effects on the heat conduction and thermal transmittance coefficients. However, the combined effect of corrugate geometry and ambient temperature was not statistically significant. Circular grooving improved the thermal performance of CLT panels, which were judged to be suitable for structural applications requiring thermal insulation.

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INTRODUCTION

Lumber, a forest product produced worldwide, is among the most widely used natural materials for construction (García-Navarro *et al*. 1996; Ramage *et al*. 2017). This use is also widespread in the wood structural applications and furniture manufacturing sectors.

In the early 20th century, the vast majority of building materials consisted of mineral-based concrete-reinforced materials (Brandner *et al*. 2016). However, beginning in the 2000s, this trend shifted with the production of engineered mass timber products (MTPs). Consequently, wood began to be preferred over mineral-based concrete materials (Schickhofer *et al*. 2010). Engineered Mass Timber products (MTPs), produced from softwood and hardwood, including particleboard, plywood, fiberboard, oriented strand board (OSB), laminated veneer lumber (LVL), glued laminated timber (Glulam), cross-laminated timber (CLT), Nailed Laminated Timber (NLT), and Structural Composite Lumber (SCL), and their use, particularly in structural applications, continues to grow

(Zhou *et al*. 2017; Hua *et al*. 2022). The production of wood-based engineered products has gained importance for the more rational use of forest products in line with the rate of global population growth (Bülbül *et al*. 2024). At the same time, societies aiming to ensure a green future are prioritizing forest products in construction applications, particularly in the building sector; and, in tandem with technological advancements, are further developing practices for obtaining forest-based construction products to ensure long-term sustainability (Koppelhuber *et al*. 2017; Malo *et al*. 2016; Bettarello *et al*. 2021; De Araujo *et al*. 2023).

Wood is a readily available, renewable, and reusable material that is easy to process (Algın *et al*. 2016). Along with these advantages, it also has certain structural disadvantages, such as being anisotropic and hygroscopic. Therefore, engineered mass timber products aim to minimize the disadvantages inherent in the structure of wood while also ensuring the more efficient use of forest products.

In general, the use of wood and wood-based composite materials focuses on products resulting from advancements in adhesive and lamination technologies (Schmidt *et al*. 2019). CLT—one such product and the subject of this study—has become a highly regarded building material, particularly in wood-based structural applications, due to its many properties, including light weight, ease of installation, and good insulation values (Saputra *et al*. 2024).

CLT, an engineered wood product, is manufactured by bonding or nailing together wood lamellas so that their grain directions are perpendicular to one another, forming at least three layers (Chen 2011; Gagnon and Pirvu 2011). With thicknesses ranging from 16 to 51 mm and widths from 60 to 240 mm, the lumber is used to produce CLT consisting of 3, 5, 7, or more odd-numbered layers as needed; the thicknesses of these CLT panels range from 50 mm to 500 mm, with lengths up to 20 m and widths up to 3 m (Mohammad *et al*. 2013; Brandner *et al*. 2016; Kurzinski *et al*. 2022). The adhesives used in the production of such industrial lumber, such as CLT, are primarily formaldehyde-based phenol-resorcinol (PRF), melamine-urea (MUF), emulsion polymer isocyanate (EPI), and polyurethane (PUR) adhesives. Consequently, the bonding performance of CLT panels varies depending on the compatibility between the selected adhesive type and the wood surface (Li *et al*. 2021). The quality of the bond between CLT lamellas will affect stress transfer between them (Yusoh *et al*. 2020). Poor bonding quality leads to failure at the bond line rather than a reduction in the mechanical strength of CLT panels (Sikora *et al*. 2016; O'Ceallaigh *et al*. 2018).

Softwoods, such as spruce, pine, and fir are primarily used in CLT production (Dong *et al*. 2023). However, given the high current demand for structural lumber, various studies are being conducted to investigate the suitability of fast-growing and hardwood species for CLT panel production (Srivaro *et al*. 2019; Das *et al*. 2023). In particular, because compressive and tensile stresses are lower in the middle layers of CLT panels, hardwood species, such as eucalyptus (Pereira and Calil 2019) and poplar, can be used. Consequently, meeting the growing demand for industrial lumber in wood structural applications helps alleviate the pressure on natural forests caused by lumber harvesting.

CLT was first developed in Austria in the 1990s as a primary construction material for structural applications. Due to their specific strength and, most importantly, their sustainability, CLT panels have begun to replace traditional construction materials such as steel and concrete. Global usage of CLT, which stood at 50,000 m^3 in 2000, reached 625,000 m^3 in 2014, and is projected to rise to 3,000,000 m^3 by 2025, with this figure continuing to rise daily (Brandner *et al*. 2016; Muszynski *et al*. 2017; Liang *et al*. 2022).

CLT panels are used in a variety of applications, including wall, roof, and floor panels, as well as bridge deck and girder elements; they are also used in the construction of high-rise buildings that combine CLT and solid wood (Schubert *et al*. 2010; Xiong *et al*. 2016).

In recent years, the use of wood has become quite widespread worldwide, particularly in the construction sector—especially in countries that traditionally use wood as a structural element. CLT—a leading industrial material in structural wood applications—has a more stable structure (expanding only one-fifth as much as solid wood in the tangential direction) and, due to its high carbon sequestration capacity, has become a preferred choice for the construction of mid- and high-rise wooden buildings, particularly in modern architecture (Lehmann 2012; Pereira and Calil 2019).

As a result of rapid industrialization and population growth, forest products have rapidly declined due to increasing demand. To prevent this decline, planting tree species with high growth potential—particularly those used in the production of various wood-based engineering products, such as CLT panels—is of great importance (Shukla 2019). Another negative factor resulting from global population growth is the rapid depletion of existing energy resources. However, developed countries, in particular, prioritize thermal insulation in structural applications to ensure the sustainability of energy efficiency (Gu and Zink-Sharp 2005). Consequently, CLT panels used in wood-based structural applications exhibit thermal insulation capabilities that vary depending on density, fiber orientation, wood species, and moisture content. In addition to their mechanical and physical strength, the thermal insulation values of CLT panels are another sought-after characteristic.

The aim of this study was to improve the thermal insulation properties of CLT produced from Scots pine and poplar wood—which have high growth potential—using a core layer composed of corrugates of various geometric shapes. Consequently, thermal insulation properties—specifically the thermal conductivity coefficient (λ) and the U-value—were investigated and determined under various temperature conditions that have not been extensively studied in the literature.

EXPERIMENTAL

Materials and Methods

In this study, Scots pine (*Pinus sylvestris* L.) and poplar (*Populus*) wood were used. The lumber used in the study was randomly selected to meet first-class lumber specifications, taking into account criteria, such as straight grain knot-free status, freedom from reaction wood decay, and damage caused by insects and fungi. Table 1 lists some characteristics of the wood species used in the manufacture of CLT panels and the adhesives used as binders.

Table 1. Properties of Materials Used in the Production of CLT Boards

Material Name	Dimensions	Density (g/cm³)	Moisture Content (%)
Scots Pine Wood	20 x 80 x 400 mm	0.54	11.3
Poplar Wood	20 x 80 x 400 mm	0.41	12.4
Polyurethane (PUR) Glue	100 to 120 g/m²	1.1	

In this study, poplar wood was used in the core layer of the CLT panels, while Scots Pine wood was used in the surface layers. The production process for the three-layer CLT panels began with conditioning poplar and Scots pine wood pieces, measuring 20 mm x 80 mm x 400 mm, in a climate chamber at a temperature of 20 °C and 65% relative humidity until they reached a constant weight. The wood pieces were left in the acclimatization chamber for an average of 7 days to reach hygroscopic equilibrium. Polyurethane adhesive (100 to 120 g/m²) was applied to the edges of the conditioned solid wood pieces, which were then placed side-by-side and glued together. The thickness of the 20 mm x 400 mm x 400 mm Scots Pine and poplar wood panels obtained by side-by-side joining was planed down to 16 mm using a Netmak thickness planer. Subsequently, the top and bottom surfaces of the 16-mm-thick poplar panels were machined with predefined geometric corrugates (circular, rectangular, and trapezoidal) on a Smart Machine brand computer numerical control (CNC) surface machining machine, as shown in Fig. 1, to create the middle layer.

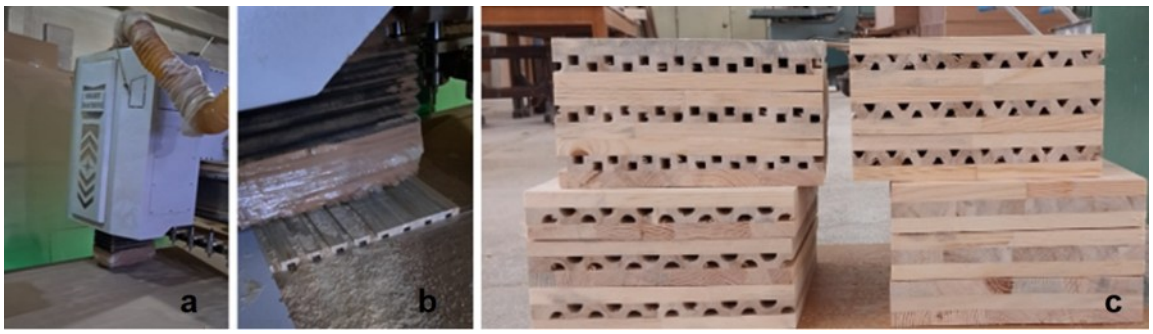
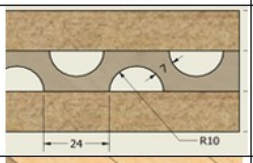
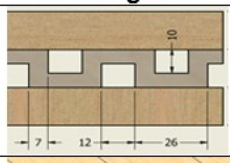
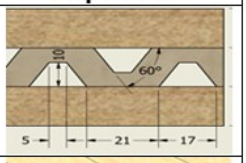
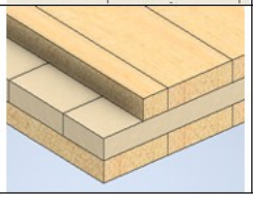
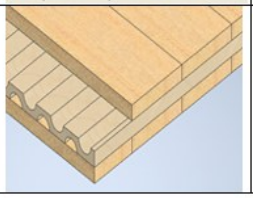
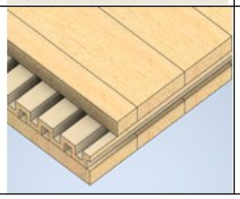
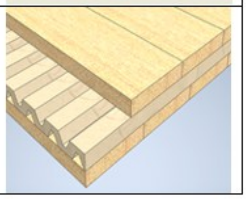


Fig. 1. CLT production: a) CNC surface machining machine, b) production of rectangular corrugated sheet metal, and c) dimensioned CLT panels

The core layers were produced by removing material at percentage levels of 10.4% for the circular corrugation, 13.3% for the rectangular corrugation, and 12.2% for the trapezoidal corrugation relative to the panel area. The geometrically corrugated core layers and the other layers of the CLT panels were conditioned in a climate chamber at 20 °C and 65% relative humidity until they reached a constant weight.

Table 2. Technical Drawings and 3D Renderings of CLT Panels

	Control	Circular	Rectangular	Trapezoidal
Front View				
3D View				

Air-dry density- moisture content

Polyurethane (PU) adhesive was applied to one surface of each of the bottom and top layers (Scots pine) of the conditioned CLT panels at a level of 100 to 120 g/m². The layers were then bonded by pressing them at a temperature of 24 °C and a pressure of 2.5 kg/cm² for 120 min, with their grain directions oriented perpendicular to the grain direction of the poplar wood panel used in the core layer. CLT panels with geometrically corrugated cores, measuring 48 mm × 400 mm × 400 mm, were produced. Technical drawings are presented in Table 2.

The air-dry density values of the 48 mm x 50 mm x 50 mm test specimens made of geometric corrugated CLT panels were determined in accordance with TS EN 338 (2016). In accordance with this standard, a total of 24 test specimens, each measuring 48 mm x 50 mm x 50 mm were prepared with 6 specimens per combination group. The prepared test specimens were conditioned at a temperature of 20 ± 2 °C and a relative humidity of 65%. An image showing the conditioning of the test specimens in the climate chamber is provided in Fig. 2.



Fig. 2. Conditioning of test specimens for geometric corrugated CLT panels

The dimensions of the samples were measured using a digital caliper with a sensitivity of ± 0.01 mm, and their volumes were calculated. The density was then calculated using Eq. 1,

$$\delta_{12} = \frac{m_{12}}{V_{12}} \quad (1)$$

where δ_{12} is the air-dry density (g/cm^3), m_{12} is the air-dry mass (g), and V_{12} is the air-dry volume (cm^3). The method specified by this standard is based on calculating the percentage difference between the mass of the CLT samples immediately after being cut and their mass after being dried at 103 ± 2 °C until a constant mass is reached. The constant mass is considered achieved when the difference between two successive measurements, a balance with a precision of 0.01 g, is less than 0.1%. The calculation is performed according to Eq. 2,

$$r = \frac{m_r - m_0}{m_0} x\ 100 \quad (2)$$

where r is the moisture content (%), m_r is the mass of moist sample (g), and m_0 is the mass of the completely dry sample (g).

Thermal conductivity coefficient (λ) and thermal transmittance coefficients (U)

To determine the thermal transmittance coefficients and thermal conductivity, 12 test specimens measuring 30 cm x 30 cm—three for each test group—were prepared in accordance with TS EN 12667 (2003). To determine the characteristic properties of the prepared samples under three different climatic conditions, they were first placed in a conditioning chamber set at a temperature of 20 °C and a relative humidity of 65% until they reached a constant weight. Once this equilibrium was attained, the necessary measurements were performed on the specimens, yielding data for the first climatic condition.

For the second condition, the temperature and relative humidity in the conditioning chamber were adjusted to 40 °C and 35%, respectively; the specimens were kept in this environment until they reached a constant weight. Measurements were then taken, providing data for the second climatic condition. Finally, the conditioning chamber was set to a temperature of 0 °C and a relative humidity of 50%. The specimens were held in this environment until they reached a constant weight, at which point the final measurements were conducted, yielding data for the third climatic condition. The conditioned test samples were removed from the climate chamber one by one and placed in a Linseis HFM 300 test device that had been conditioned to different temperature environments (0, 20, and 40 °C) as shown in Fig. 3, to determine the thermal transmittance and thermal conductivity coefficients. actual ambient temperatures vary globally across different locations and over the course of days and seasons, this experiment was conducted using the three different temperature environments specified above.

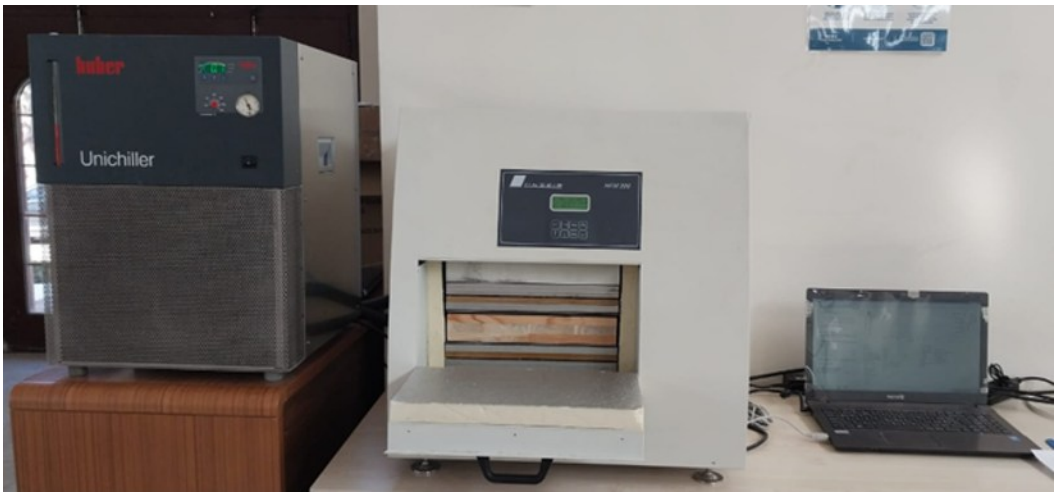


Fig. 3. Equipment used to determine of the thermal conductivity and thermal transmittance coefficients of CLT panels

Data Analysis

The SPSS 26 and MSTAT-C programs were used to analyze the data obtained from experimental methods. Using these programs, multivariate analysis of variance (MANOVA) was performed, followed by multiple comparison tests at the 95% confidence level.

RESULTS AND DISCUSSION

Moisture Content and Air-dried Density Values for Geometric Corrugated CLT Panels

The moisture content values for CLT panels with corrugates of various geometrically shapes are presented in Table 3.

Table 3. Moisture Content Values for CLT Panels with Geometric-shaped corrugates

Name of CLT Panel	N	X_{mean} (%)
Control	6	8.37
Circular	6	9.11
Rectangular	6	10.31
Trapezoidal	6	9.67

It was found that the moisture content of panels with geometric-shaped corrugates was higher than that of the control group samples. It can be said that this increase resulted from the geometric-shaped grooving process applied to the core layers of the CLT panels, which led to an increase in the surface area exposed to air within the panels. Statistical data on the air-dry density values of CLT panels with a geometric-shaped corrugated middle layer under conditions of 20 °C and 65% relative humidity are presented in Table 4.

Table 4. Statistical Data on the Air-dry Density Values of Geometric Corrugated CLT Panels

Name of CLT Panel	N	X_{min}	X_{max}	X_{mean} (HG)	Std. Dev.
Control	6	0.50	0.57	0.55 (A)	0.030
Circular	6	0.45	0.52	0.47 (B)	0.025
Rectangular	6	0.45	0.50	0.47 (B)	0.017
Trapezoidal	6	0.44	0.48	0.46 (B)	0.016

LSD: 0.03 g/cm^3; HG: Homogeneity groups

When examining the average density values of CLT panels with geometric corrugated core layers, it was found that the lowest air-dry density value (0.46 g/cm^3) was observed in the trapezoidal- corrugated panel, while the highest air-dry density value (0.55 g/cm^3) was found in the control group panel. Consequently, it was determined that the air-dry density values of the geometric corrugated CLT panels were approximately 15% lower than those of the control group panels. Based on this result, an MANOVA was conducted to determine the effect of geometric-shaped grooving applied to the core layers on the average air-dry densities of the CLT panels, and the results are presented in Table 5.

Table 5. Results of a Multiple Variance Analysis Conducted to Determine the Effect of Geometric Grooving Applied to the Core Layer of CLT Panels on the Panels' Air-dry Density Values

Source	Sum of Squares	DF	Mean Square	F Value	Sig. ($p < 0.05$)
Geometric Shape	0.028	3	0.009	18.67	0.000
Error	0.010	20	0.001		
Corrected Total	5.751	24			
Total	0.038	23			

According to Table 5, the geometric-shaped grooving applied to the middle layers of CLT panels had a significant effect (F: 18.67; $p < 0.05$) on the panels' air-dry density values. The homogeneity groups for the Duncan test, conducted to determine the levels of between-group differences for the geometric-shaped grooving, which was found to have a significant effect, are presented in Table 4. Accordingly, it was determined that there was no significant difference in the air-dry density values among CLT panels with the geometric-shaped middle layer; however, the air-dry density values of CLT panels with this structure were found to differ significantly from those of the control group panel. It has been reported that perforation applied to the middle layers of the three- and five-layer CLT panels they produced, at percentages of 10% and 20%, resulted in a decrease in panel density (Çavuş *et al.* 2023). In another study, a 20% perforation percentage was found to reduce the thermal transmittance coefficient and thermal conductivity of the panels (Kaya *et al*. 2026). Similarly, hybrid CLT panels have been reported to provide improved thermal insulation performance compared with concrete when used in structural wall applications (Kang and Kim 2025). The density of wood, which has a porous structure, affects its mechanical and technological properties. In particular, it has been observed that mechanical properties increase as density increases (Bozkurt and Erdin 1995; Srivaro *et al*. 2021). Similarly, CLT wall panels produced from softwood species exhibit higher ductility ratios than those produced from high-density wood species when subjected to lateral loads (Tran and Jeong 2021). However, the use of wood species with a density lower than 0.35 g/cm³ in the production of CLT panels is not considered appropriate (APA 2012). Therefore, the mechanical and technological properties of CLT panels depend on the density of the wood species used in their production.

Thermal Insulation Values for CLT Panels

Statistical data on the thermal conductivity and thermal transmittance coefficients are given in Table 6.

Table 6. Thermal Conductivity and Thermal Transmittance Coefficients of CLT

	Middle Layer	Ambient Temperature (°C)	N	X_{min}	X_{max}	X_{mean}	Std. Dev.
Thermal Conductivity Coefficient (W/m.K)	Control	0	3	0.095	0.103	0.099	0.002
		20	3	0.093	0.101	0.097	0.003
		40	3	0.123	0.131	0.128	0.001
	Circular	0	3	0.088	0.097	0.092	0.004
		20	3	0.084	0.093	0.088	0.001
		40	3	0.112	0.120	0.116	0.003
	Rectangular	0	3	0.090	0.099	0.094	0.006
		20	3	0.093	0.101	0.097	0.009
		40	3	0.114	0.123	0.119	0.004
	Trapezoidal	0	3	0.092	0.101	0.097	0.007
		20	3	0.090	0.099	0.095	0.011
		40	3	0.115	0.123	0.119	0.001
	Middle Layer	**Ambient Temperature (°C)**	**N**	X_{min}	X_{max}	X_{mean}	**Std. Dev.**
Thermal transmittance coefficients (W/m².K)	Control	0	3	1.958	2.142	2.050	0.038
		20	3	1.893	2.077	1.985	0.055
		40	3	2.511	2.695	2.603	0.008
	Circular	0	3	1.823	2.007	1.915	0.054
		20	3	1.717	1.901	1.809	0.013
		40	3	2.262	2.446	2.354	0.012
		0	3	1.869	2.053	1.961	0.143

	Rectangular	20	3	1.905	2.089	1.997	0.184
		40	3	2.329	2.513	2.421	0.088
	Trapezoidal	0	3	1.902	2.086	1.994	0.078
		20	3	1.848	2.032	1.940	0.135
		40	3	2.344	2.528	2.436	0.008

According to Table 6, the thermal conduction (W/m·K) and thermal transmittance (W/m²·K) coefficients, which depend on the independent variables—namely, the geometry of the intermediate layer corrugates and ambient temperature—were statistically different from one another. However, the results of the MANOVA conducted to determine whether the effects of the intermediate layer geometry and ambient temperature—which could influence the differences in the thermal conduction and thermal transmittance coefficients—were statistically significant and are presented in Table 7.

Table 7. Results of a Multivariate Analysis of Variance Regarding the Thermal Conductivity (*λ*) and Thermal Transmittance (*U*) Values of CLT Panels

	Source	**Sum of Squares**	**df**	**Mean Square**	**F**	**Sig. (p < 0.05)**
Thermal conductivity (W/m.K)	Geometric shape (A)	0.000	3	0.000	9.309	0.000
	Ambient temperature (B)	0.005	2	0.003	205.819	0.000
	A x B	0.000	6	1.751E-5	1.410	0.252
	Error	0.000	24	1.242E-5		
	Total	0.392	36			
	Corrected Total	0.006	35			
	Source	**Sum of Squares**	**df**	**Mean Square**	**F**	**Sig. (p < 0.05)**
Thermal transmittance (W/m²·K)	Geometric shape (A)	0.157	3	0.052	8.78	0.000
	Ambient temperature (B)	1.991	2	0.996	167.37	0.000
	A x B	0.040	6	0.007	1.12	0.387
	Error	0.143	24	0.006		
	Total	164.448	36			
	Corrected Total	2.331	35			

According to the MANOVA test, the effects of geometric shaped grooving applied to the core layers of CLT panels with a geometric corrugated core layer, as well as different ambient temperatures, on the thermal conductivity and U-values were statistically significant ($p < 0.05$). However, according to the MANOVA, the two-way interaction between the geometric grooving and ambient temperature had no statistically significant effect ($p > 0.05$) on the thermal conductivity and thermal transmittance coefficients of the CLT panels. Based on the results of the MANOVA test, Duncan's test was performed to identify differences between groups of variables with statistically significant effects, and homogeneous groups were identified; the results are presented in Tables 7 and 8.

Table 8. Homogeneity Groups of Heat Conduction and Thermal Transmittance by Corrugation Shape

Thermal Conductivity				Thermal Transmittance			
Middle layer	**N**	**$\bar{X}$ (W/m.K)**	**HG**	**Middle layer**	**N**	**$\bar{X}$ (W/m².K)**	**HG**
Control	9	0.108	A	Control	9	2.213	A
Circular	9	0. 099	C	Circular	9	2.026	C
Rectangular	9	0.103	B	Rectangular	9	2.126	B
Trapezoid	9	0.104	B	Trapezoid	9	2.123	B
LSD: 0.0034				LSD: 0.073			

According to the results of the Duncan test, applying geometric shaped corrugates to the core layer of CLT panels resulted in a significant decrease (improvement) in the panels' thermal conductivity and U-value. Furthermore, among the circular, rectangular, and trapezoidal corrugates applied to the core layers of CLT panels, it was found that the use of circular corrugates, in particular, resulted in a distinct and significant improvement in the thermal conductivity and U-values.

The literature indicates that the lowest thermal conductivity coefficient for poplar wood is 0.090 W/m·K, while for pine wood, depending on the species, it ranges from 0.129 W/m·K to 0.132 W/m·K (Çavuş *et al*. 2019). The thermal conductivity of wood varies depending on the tree species, density, moisture content, and direction of heat flow. In particular, studies have found a linear relationship between the wood density and thermal conductivity (Suleiman *et al*. 1999; Mauranen *et al*. 2015; Çavuş *et al*. 2019). In these studies, it was found that the thermal conductivity values of laminated wood composite materials decreased following various geometric grooving and perforation processes performed on the low-density material used in the middle layers (Bülbül and Keskin 2023; Kaya 2023). In this context, because the thermal conductivity of air is 0.024 W/m·K (Peron *et al*. 2020), it can be concluded that the geometric grooving allows air to enter the existing voids, resulting in a reduction in the thermal conductivity of CLT panels.

According to other studies, the thermal conductivity (λ) coefficients for concrete and brick walls with a thickness of 16 mm are 0.9 and 1.16 W/m·K, respectively (El Fgair *et al*. 2015; Asadi *et al*. 2018). Consequently, if the thermal conductivity of a material used in structural applications is less than 0.15 W/m·K; this indicates that the material is suitable for thermal insulation applications (JIS A1412 1994).

As energy efficiency and sustainability become increasingly important in construction, this study investigated the effect of geometric grooves in the core layer of CLT wall panels on their thermal performance. The results showed that these grooves significantly reduced the thermal conductivity of the panels. Since the measured thermal conductivity values were below the reference limit, the grooved CLT panels were found to be promising materials for thermal insulation in wooden buildings.

In structural applications, another key indicator for materials used for thermal insulation is the "U-value," which represents the thermal transmittance coefficient; specifically, it is the heat flux rate at equilibrium, divided by the temperature difference between the two surfaces of the wall and the wall's surface area (Song *et al*. 2024). Consequently, a lower thermal conductivity coefficient of a material results in lower heat loss.

Kawasaki and Kawai (2006) reported that the thermal transmittance of fiberboard-core sandwich panels increased from 5.4 to 8.4 W/m²·K as density increased from 310 to 460 kg/m³. Similarly, low-density fiberboards with densities of 140 and 250 kg/m³ had

thermal transmittance values of 4.1 and 5.2 W/m²·K, respectively. These findings indicate a positive relationship between density and thermal transmittance. A similar trend was observed in the present study.

Table 9. Homogeneity Groups of Heat Conduction and Thermal Conductivity by Ambient Temperature

Thermal Conductivity				Thermal Transmittance			
Ambient Temperature (°C)	N	$\bar{X}$ (W/m·K)	HG	Ambient Temperature (°C)	N	$\bar{X}$ (W/m²·K)	HG
0	12	0.095	B	0	12	1.980	B
20	12	0.094	B	20	12	1.933	B
40	12	0.120	A	40	12	2.454	A
LSD: 0.029				LSD: 0.064			

According to Table 9, no significant difference was found in the thermal conductivity and thermal transmittance coefficients of geometric corrugated CLT panels at temperatures ranging from 0 to 20 °C. However, the analysis revealed that the thermal conductivity and thermal transmittance coefficient values obtained at 40 °C were significantly higher than those obtained at temperatures between 0 and 20 °C.

Srivaro *et al.* (2021) and Kuo *et al.* (2023) have noted a positive relationship between thermal conductivity values and ambient temperatures; as ambient temperature increases, thermal conductivity coefficients also increase in proportion to density, and this increase occurs at any given ambient temperature In another study, it was found that the thermal conductivity coefficients of Scots pine, chestnut, and oak wood differ at 10, 20, and 40 °C, and that the thermal conductivity coefficient at 40 °C is higher for all three wood species. In the same study, it was also found that the thermal transmittance coefficients exhibited a variation parallel to that of the thermal conductivity coefficients (Altunok *et al*. 2023). Therefore, the results of previous studies support the data on thermal conductivity and thermal transmittance coefficients obtained in this study.

CONCLUSIONS

1. *Moisture Content and Air-Dry Density:* The geometric corrugated cross-laminated timber (CLT) panels exhibited higher moisture content than the control group. This increase can be attributed to the larger internal surface area created by the corrugates, which provides a greater area for moisture exchange with the surrounding air. Geometric grooving of the middle layer significantly reduced the air-dry density of the CLT panels. The average density decreased from 0.55 g/cm³ in the control group to 0.46 to 0.47 g/cm³ in the corrugated panels.
2. *Thermal Conductivity and Thermal Transmittance:* All corrugated CLT panels exhibited lower thermal conductivity values than the control group. Among the tested configurations, the circular- corrugated panel showed the lowest average thermal conductivity, measuring 0.099 W/m·K. This panel also demonstrated the lowest (best) thermal transmittance performance, with an average value of 2.026 W/m²·K. Furthermore, the thermal conductivity values of all CLT panels remained below the 0.15 W/m·K threshold, confirming their suitability for thermal insulation applications. Overall, the circular-corrugated middle layer provided the best thermal performance.

3. *Effect of Ambient Temperature:* No statistically significant differences were observed in thermal conductivity or thermal transmittance between 0 °C and 20 °C. However, both properties increased significantly at 40 °C, indicating that elevated ambient temperature adversely affected the thermal performance of the panels
4. Future studies should investigate 5-layer and 7-layer CLT panels to determine whether similar improvements in thermal performance can be achieved in thicker panel configurations.
5. The influence of geometric grooving on the mechanical properties of CLT panels, including bending strength, compression strength, shear strength, and connection performance, should be comprehensively evaluated.
6. Field-scale experiments and numerical simulations are recommended to evaluate the contribution of low-density core layers and geometric voiding to building-scale energy savings in energy-efficient timber construction systems.

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