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Enhancing the Thermal and Acoustic Performance of Cross-Laminated Timber Panels through Perforation

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The increasing need for energy-efficient and acoustically optimized buildings has positioned cross-laminated timber (CLT) as a competitive material in sustainable construction. This study investigates the impact of perforation techniques on the thermal and acoustic performance of CLT panels produced from Scots pine (*Pinus sylvestris* L.), Uludağ fir (*Abies bornmülleriana* Mattf.), and sessile oak (*Quercus petraea* L.). Panels were manufactured in three- and five-layer configurations, incorporating perforation ratios of 10% and 20% in the internal layers. Experimental results demonstrated that increasing perforation ratios led to a decrease in thermal conductivity and transmittance, while significantly improving sound absorption coefficients. For instance, panels with 20% perforation exhibited a notable reduction in sound transmission, contributing to enhanced indoor acoustic comfort. These findings underline the potential of perforated CLT panels as multifunctional elements in both residential and commercial buildings. The study highlights the potential global impact of integrating such material innovations into sustainable construction practices, particularly in urban environments demanding high thermal efficiency and noise control.

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Introduction

Cross-laminated timber (CLT) has emerged in recent years as an innovative engineered product in the construction industry, known for its sustainability and structural performance. The cross-layering of timber panels enhances their strength and dimensional stability. Developed in the early 1990s, CLT has gained widespread use globally, particularly in Europe, and is now favored for both low-rise and high-rise buildings (Brandner *et al.*, 2016). It has also become a preferred material in energy-efficient designs (Younis and Dodoo, 2022).

CLT offers an environmentally friendly alternative to traditional materials like steel and concrete due to its reduced carbon footprint and aesthetic appeal (Lan *et al.*, 2019). In addition, its natural appearance and flexibility in design have been appreciated in modern timber architecture (Lolli *et al.*, 2019). Its ability to combine structural efficiency with sustainable practices makes CLT a suitable material for modern construction approaches (De Araujo and Christoforo, 2023). Recent advancements in CLT technology have introduced alternative lamination strategies aimed at optimizing structural performance and resource utilization. In this

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context, Santos *et al.* (2024) proposed a novel approach through the development of alternated cross-laminated timber (aCLT) panels, wherein the lamellae in adjacent layers are intentionally misaligned to modify mechanical behavior and deformation characteristics.

Carbon footprint reduction has become a critical aspect of sustainable material research, particularly in the construction sector. According to a recent study, the utilization of agricultural residues in building materials presents a viable method for enhancing sustainability and reducing environmental impact (Stefanidou *et al.*, 2023). That study explored the innovative use of lavender waste as an additive in traditional mortar formulations, demonstrating how organic by-products can contribute to mechanical strength, durability, and eco-friendliness. The findings suggest that lavender waste can improve certain properties of mortar mixtures, offering a sustainable alternative by repurposing agricultural residues and thereby contributing to carbon footprint reduction in construction applications.

The construction industry contributes significantly to global carbon emissions, with concrete and steel having particularly large carbon footprints. In contrast, CLT can reduce a building's carbon footprint by up to 40% through its natural carbon storage capabilities (Jeleč *et al.*, 2018). Timber retains carbon throughout its lifecycle, providing an effective solution to offset carbon emissions in construction, which is especially relevant as environmental regulations become stricter (He *et al.*, 2021). In addition to its carbon sequestration potential, CLT also offers benefits such as recyclability and biodegradability, further reducing the ecological impact of construction projects (Gagnon and Pirvu, 2011).

Prefabricated CLT panels shorten construction times, reduce costs, and minimize material waste (Salonvaara and Desjarlais, 2024). Their lightweight nature requires less foundation depth compared to concrete or steel, making CLT especially suitable for urban construction and retrofitting projects (Valluzzi *et al.*, 2021). Prefabrication also speeds up the assembly process and reduces labor costs, contributing to more efficient project timelines (Nakano *et al.*, 2020). Additionally, CLT offers superior fire resistance when compared to conventional wood-based products due to its thick cross-layers, which char slowly under fire conditions and protect the structural core (Navaratnam *et al.*, 2020; Zeitz *et al.*, 2019).

One of CLT's key advantages is its thermal insulation properties. Its natural cellular structure resists heat transfer, with thermal conductivity values varying depending on wood species and panel thickness (Gu and Zink-Sharp, 2005). These values make CLT an energy-efficient option in both hot and cold climates. Moreover, CLT panels exhibit low U-values, which mean reduced heat loss in winter and heat gain in summer, thereby improving building energy performance (Öztürk *et al.*, 2017). Such properties align with passive house standards that aim to minimize energy consumption while maintaining high indoor comfort levels (Yang *et al.*, 2014; Yu *et al.*, 2021). In particular, buildings constructed with CLT require less heating and cooling energy, further supporting sustainability goals (Ullah and Kim, 2017).

Recent studies have highlighted the growing significance of perforation techniques in engineered wood products, particularly in optimizing sound absorption, thermal insulation, and thermal transmittance in cross-laminated timber (CLT) panels (Hrčka and Babiak, 2017). Perforation modifies internal air pockets in wood-based panels, influencing heat transfer mechanisms and reducing thermal conductivity (Shan *et al.*, 2023). It also enhances acoustic performance by acting as a resonator that improves sound absorption in mid and high frequencies (Bettarello *et al.*, 2021).

Despite these benefits, the effects of perforation on CLT panels are still insufficiently explored. Most existing studies address thermal and acoustic behavior in solid configurations without internal modifications (Caniato *et al.*, 2021; Rämäkkö, 2021). The effect of parameters such as perforation geometry, depth, and distribution on thermal transmittance and acoustic insulation remain understudied (Vardaxis *et al.*, 2022).

Comparative evaluations between perforated and non-perforated CLT panels are also lacking in the literature, especially regarding energy efficiency and sound control (Liu *et al.*, 2018). To bridge this gap, the present study investigates the thermal and acoustic properties of perforated CLT panels produced using different wood species and perforation ratios. It aims to provide insight into how perforation affects performance in terms of heat resistance and sound absorption (Kang *et al.*, 2024).

CLT's intrinsic acoustic properties make it ideal for applications requiring high sound insulation, such as schools and urban housing (Zhang *et al.*, 2020; Ju *et al.*, 2019). When perforated, its absorption coefficients can be further improved, especially at 1000 Hz and above (Logawa, 2017; Mayer *et al.*, 2020). Enhanced low-frequency absorption can also be achieved through layered resonance systems. High-frequency performance benefits are consistently observed in CLT panel applications (Zhigulina and Ponomarenko, 2018).

Given the growing emphasis on sustainable construction, CLT's low carbon emissions, insulation capabilities, and acoustic performance solidify its value in green building (Oldfield, 2019; Gasparri, 2022). Advances in digital fabrication and BIM technologies are expected to further improve the material's efficiency and cost-effectiveness (Halhoul Merabet *et al.*, 2021; Khavari *et al.*, 2016). With rising global standards for low-impact construction, CLT is a key solution to meet sustainability targets (Mi *et al.*, 2015).

Moreover, CLT receives high scores in sustainability certifications such as LEED, BREEAM, and DGNB due to its energy and environmental performance, particularly in Europe, North America, and emerging regions such as Australia (Rämäkkö, 2021).

The use of CLT in high-rise buildings has expanded in recent years. Countries such as Canada, Austria, and the United States lead in implementing tall timber construction. Projects like the 18-storey Brock Commons Tallwood House in Vancouver showcase the benefits of carbon storage and rapid construction. Similarly, the HoHo Tower in Austria illustrates the synergy of timber with sustainability goals (Gilbert *et al.*, 2020). These examples confirm that CLT supports global decarbonization efforts in the building sector (Balasbaneh and Sher, 2021; Svobodová and Hlaváčková, 2023).

This study aims to assess how perforation techniques influence the thermal insulation and sound absorption performance of CLT panels, considering different wood species, layer configurations, and perforation ratios. It is hypothesized that introducing perforations enhances thermal resistance and acoustic efficiency by forming internal air cavities, especially effective at mid-to-high frequencies. The findings are intended to guide architects, engineers, and sustainability-focused designers, particularly in regions such as Europe, North America, and Turkey, where eco-friendly building solutions and urban noise control are priorities.

Material and methods

1. Materials

In this study, both coniferous and broadleaf tree species were used in the production of cross-laminated timber (CLT). In particular, Scots pine (*Pinus sylvestris* L.) and Uludağ fir (*Abies bornmülleriana* Mattf.) were selected as preferred coniferous species, in view of their widespread usage. Sessile oak (*Quercus petraea* L.) was chosen among the broadleaf species. These tree species were selected due to their structural properties and their local market availability. Scots pine (*Pinus sylvestris*), Uludağ fir (*Abies bornmülleriana*), and sessile oak (*Quercus petraea*) are known for their mechanical strength and resistance to environmental factors, making them suitable for construction purposes. Their widespread presence in the regional market contributes to lower transportation costs and enhances their sustainability by reducing the carbon footprint associated with material sourcing. The choice of these species also aligns with local forestry practices, which emphasize sustainable harvesting and the promotion of renewable resources in building materials. Furthermore, these wood species have been widely used in engineered wood products like cross-laminated timber (CLT) due to their compatibility with modern construction technologies and long-term durability.

Timbers were obtained from a forest products supplier located in Siteler region of Ankara by a random sampling method. Care was taken to ensure that the wood material was free from defects such as knots, cracks, reaction wood and fiber defects that could affect

Table 1. Experimental setup for the 3 layer CLT panels

Abbreviation	Perforation ratio	Layers		
		Outer layer	Inner	Outer layer
3.0.PPP	0%	*Scots Pine*	*Scots Pine*	*Scots Pine*
3.0.PFP	0%	*Scots Pine*	*Uludağ Fir*	*Scots Pine*
3.10.PPP	10%	*Scots Pine*	*Scots Pine*	*Scots Pine*
3.10.PFP	10%	*Scots Pine*	*Uludağ Fir*	*Scots Pine*
3.20.PPP	20%	*Scots Pine*	*Scots Pine*	*Scots Pine*
3.20.PFP	20%	*Scots Pine*	*Uludağ Fir*	*Scots Pine*
3.0.OPO	0%	*Sessile Oak*	*Scots Pine*	*Sessile Oak*
3.0.OFO	0%	*Sessile Oak*	*Uludağ Fir*	*Sessile Oak*
3.10.OPO	10%	*Sessile Oak*	*Scots Pine*	*Sessile Oak*
3.10.OFO	10%	*Sessile Oak*	*Uludağ Fir*	*Sessile Oak*
3.20.OPO	20%	*Sessile Oak*	*Scots Pine*	*Sessile Oak*
3.20.OFO	20%	*Sessile Oak*	*Uludağ Fir*	*Sessile Oak*

Table 2. Experimental setup for the 5 layer CLT panels

Abbreviation	Perforation ratio	Layers				
		Outer layer	2. layer	3. layer	4. layer	Outer layer
5.0.PPPPP	0%	*Scots Pine*	*Scots Pine*	*Scots Pine*	*Scots Pine*	*Scots Pine*
5.0.PFFFP	0%	*Scots Pine*	*Uludağ Fir*	*Uludağ Fir*	*Uludağ Fir*	*Scots Pine*
5.10.PPPPP	10%	*Scots Pine*	*Scots Pine*	*Scots Pine*	*Scots Pine*	*Scots Pine*
5.10.PFFFP	10%	*Scots Pine*	*Uludağ Fir*	*Uludağ Fir*	*Uludağ Fir*	*Scots Pine*
5.20.PPPPP	20%	*Scots Pine*	*Scots Pine*	*Scots Pine*	*Scots Pine*	*Scots Pine*
5.20.PFFFP	20%	*Scots Pine*	*Uludağ Fir*	*Uludağ Fir*	*Uludağ Fir*	*Scots Pine*
5.0.OPPPO	0%	*Sessile Oak*	*Scots Pine*	*Scots Pine*	*Scots Pine*	*Sessile Oak*
5.0.OFFFO	0%	*Sessile Oak*	*Uludağ Fir*	*Uludağ Fir*	*Uludağ Fir*	*Sessile Oak*
5.0.OPPPO	10%	*Sessile Oak*	*Scots Pine*	*Scots Pine*	*Scots Pine*	*Sessile Oak*
5.0.OFFFO	10%	*Sessile Oak*	*Uludağ Fir*	*Uludağ Fir*	*Uludağ Fir*	*Sessile Oak*
5.0.OPPPO	20%	*Sessile Oak*	*Scots Pine*	*Scots Pine*	*Scots Pine*	*Sessile Oak*
5.0.OFFFO	20%	*Sessile Oak*	*Uludağ Fir*	*Uludağ Fir*	*Uludağ Fir*	*Sessile Oak*

the test results. In this study, the same wood species was used for all types of CLT panels to ensure consistency in material properties and eliminate variability due to species differences. Maintaining uniformity in wood species selection allowed a more controlled comparison of the effects of perforation techniques on thermal and acoustic performance.

Polyurethane (PUR) adhesive was used to manufacture CLT panels. The adhesive was supplied by Adel Kimya, which offers high quality and performance in building materials. The adhesive has the mechanical strength and bonding strength required for structural wood products and complies with the relevant standards. The properties of the 3- and 5-layer CLT panels produced in this research are presented in detail in Table 1 and Table 2.

2. CLT manufacture

The lumber used for CLT production, with dimensions of 2 cm in thickness and 10 cm in width, was first cut to lengths of 80 cm and 145 cm using a circular saw. Following this, the lumber was processed using a Weinig machine, where three key operations were performed: surface cleaning, edge trimming, and the

Fig. 1. CLT production: a) solid wood material, b) CLT pressing process, c) dimensioned CLT panels, d) conditioning of test samples

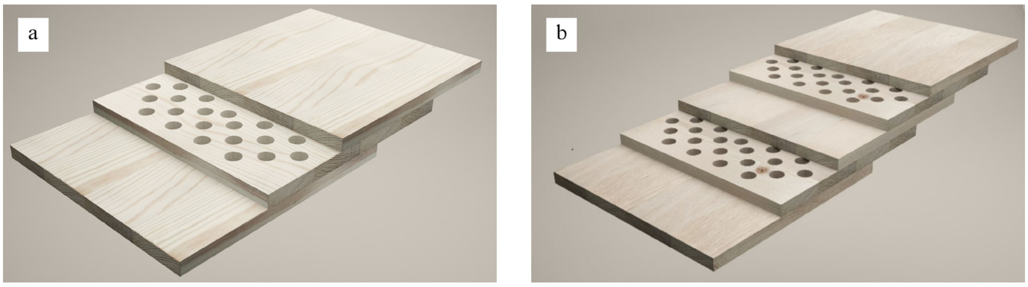


Fig. 2. Orientation of CLT panels: a) 3-layer CLT panel, b) 5-layer CLT panel

precise cutting of finger joint channels into the sides of the panels. These processes are critical for ensuring the dimensional accuracy and durability of the timber, which enhances the mechanical performance of the final CLT panels. The detailed steps of the CLT production process are illustrated in Fig. 1.

In the side-by-side joining press, solid panels measuring 40x90x1.7 cm and 76x145x1.7 cm were fabricated for the outer and intermediate layers.

In this study, polyvinyl acetate (PVAc) adhesive was used for bonding the CLT panels, in accordance with the principles outlined in TS 3891 (2019). The adhesive had a density of 1.1 g/cm³, a viscosity of 16–20 sec (DIN Cup), a pH value of 5, and an ash content of 3%, ensuring compatibility with wood bonding applications. The CLT panels were bonded using the cold pressing method, with a pressing time of 30 minutes at 20 °C, application pressure 0.8 N/mm², as specified in TS 3891 (2019). No heat was applied during the pressing process. After pressing, the panels were kept under pressure until complete adhesive curing was achieved, ensuring optimal bonding strength and structural stability. These parameters were chosen to maintain consistent adhesion quality across all CLT samples, allowing a controlled evaluation of the impact of perforation techniques on thermal and acoustic performance.

This study used perforation rates of 10% and 20% in the intermediate layers, with the aim of enhancing both the thermal and acoustic performance of the CLT panels. Fig. 2 illustrates the perforation patterns applied to the intermediate layers, showing the perforation design used in the experimental samples.

3. Air-dry density

The determination of the density of the test samples was conducted in accordance with the principles outlined in TS EN 323 (1999). The test samples for which density was to be measured were prepared with dimensions of 51x51x51 mm and 85x85x85 mm. A total of 40 samples were prepared, with 5 samples for each variable. The mass of the samples () was measured using a precision balance with a sensitivity of ±0.01 g, under conditions of 20±2 °C temperature and 65±5% relative humidity. 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 equation 1:

$$\delta_{12} = \frac{m_{12}}{V_{12}} \tag{1}$$

where:
δ_{12} : air-dry density (g/cm³)
m_{12}: air-dry mass (g)
V_{12} : air-dry volume (cm³)

This methodology is consistent with practices reported in earlier studies assessing the physical and thermal characteristics of timber panels (Švajlenka *et al.*, 2020a; Santos *et al.*, 2021), ensuring the comparability and reliability of experimental results.

4. Moisture content

The determination of the equilibrium moisture content of the test samples was conducted in accordance with TS EN 322 (1999). 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, taken 6 hours apart using a balance with a precision of 0.01 g, is less than 0.1%. This final mass is regarded as the constant mass. The calculation is performed according to equation 2.

Test samples were prepared with dimensions of 51x51x51 mm and 85x85x85 mm. The experimental samples are illustrated in Fig. 3.

$$r = \frac{m_{r-}m_0}{m_0} x100 \tag{2}$$

where:
r : moisture content (%)
m_r : mass of moist sample (g)
m_0 : mass of completely dry sample (g)

Fig. 3. Moisture content test samples

This approach is consistent with experimental practices in related studies assessing the hygrothermal behavior of wood-based construction systems (Švajlenka *et al.*, 2020a; Santos *et al.*, 2021), which report similar drying conditions and mass-based measurement procedures for moisture content determination.

5. Thermal performance

Three- and five-layer cross-laminated timber panels were produced with dimensions of 40x90 cm and 76x145 cm. Test samples were taken from these panels for the respective tests. The prepared CLTs were reduced to net dimensions for the experiments. In order to determine the heat transfer coefficients, they were reduced to dimensions of 30x30x5.1 cm and 30x30x8.5 cm, and were kept in an air conditioning chamber at 20±2 °C, 65±5% relative humidity, as shown in Fig. 1.

This sample preparation and conditioning methodology is consistent with established practices in similar studies examining the hygrothermal performance of timber-based panels (Švajlenka *et al.*, 2020a; Santos *et al.*, 2021).

6. Thermal conductivity coefficient (λ)

In determining the heat transfer coefficient, three test samples for each group were conditioned in the air conditioning cabinet at 20 °C temperature and 65% relative humidity until they reached constant weight according to the principles of TS EN 12667 (2003). For each experimental group, three specimens were conditioned in a climate-controlled chamber at 20±2 °C and 65±5% relative humidity until constant mass was achieved. After conditioning, the samples were placed between temperature-controlled plates of the LINSEIS HFM 300/3 heat flow meter apparatus. The λ-values were automatically computed using the integrated LINSEIS software system based on equation 3:

$$\lambda = \frac{q.d}{A.\Delta T} \tag{3}$$

where:
λ : thermal conductivity coefficient (W/m.K)
q: power supplied to the measuring section of the heating unit (W)
d: thickness of the test sample (mm)
A: measuring area of the test sample (m^2)
ΔT: temperature difference between the panels (°C)

This method aligns with previous experimental studies that evaluated the thermal behavior of cross-laminated and timber-based wall panels under controlled environmental conditions (Švajlenka *et al.*, 2020a; Santos *et al.*, 2021; Proença *et al.*, 2024).

7. Heat transfer coefficient (U)

The thermal transmittance coefficient (U-value) of the CLT panels was determined using the LINSEIS HFM 300/3 heat flow meter apparatus, in accordance with the TS EN 12667 (2003) standard. This method enables steady-state measurement of thermal transmittance and conductivity for flat and homogeneous construction materials.

The device operates based on Peltier-controlled temperature plates, capable of maintaining surface temperatures between –30 °C and +90 °C. During testing, the upper and lower plates were set to 35 °C and 15 °C, respectively, ensuring a consistent temperature gradient across the sample. The equipment includes 15 measurement points and allows precise temperature control and heat flow monitoring through both surfaces of the test specimen.

Test samples with dimensions up to 305 mm × 305 mm × 105 mm were placed between the plates, and measurements were taken once thermal equilibrium was achieved. The heat transfer coefficient (U) value was calculated from equation 4:

Fig. 4. Device used to determine thermal conductivity coefficients and thermal transmittance coefficients

$$U = \frac{\lambda}{d} \tag{4}$$

where:
U: thermal transmittance coefficient (W/m².K)
λ: thermal conductivity coefficient (W/m.K)
d: thickness of the test sample (mm)

Prior to testing, sample thicknesses were measured with a digital micrometer (±0.01 mm precision). The LINSEIS HFM 300/3 device was calibrated using certified reference materials traceable to national standards. The system offers a measurement accuracy of ±1% to ±3%, with repeatability of ±0.25%. Contact pressure during testing was maintained at approximately 0.25 kPa, ensuring optimal thermal contact between the plates and the sample surfaces. All experiments were conducted in a controlled laboratory environment, free from external heat or airflow disturbances, to ensure data reliability and standard compliance.

8. Sound absorption

To determine the sound absorption coefficients of the CLT panels, cylindrical samples with diameters of Q10x5.1 cm and Q10x8.5 cm were prepared using a CNC router. The samples were extracted from 30×30 cm CLT panels, and three replicates were obtained for each configuration, as illustrated in Fig. 5.

In order to determine the sound absorption coefficient of cross-laminated wooden panels, the test samples are placed linearly at one end of the impedance tube. The sound pressure resulting from the plane waves produced by the sound source is measured at two points close to the test samples. The test is performed with two microphones and is based on the method of measuring the transfer function between the signals produced by the microphones after the phase calibration between the microphones. As a result of this method, the sound absorption coefficients and impedance values of the cross-laminated wooden panels are determined. A schematic diagram of the device used to determine the sound absorption coefficient is given in Fig. 6.

The panels subjected to the test process were tested in the frequency range 50–450 Hz in the first stage and in the range 250–1600 Hz in the second stage, and the data were obtained by combining the values. The impedance tube used in determining the sound absorption coefficient is shown in Fig. 6.

The acoustic measurements were conducted using an impedance tube system (model: BSWA SW422, serial: 540017), manufactured by BSWA Technology Co., Ltd., China. The setup complies with the ASTM E1050-08 standards, which define the transfer function method using two microphones.

Fig. 5. Preparation of sound absorption test samples: a) processing of test samples on CNC machine, b) sound absorption test samples ready for testing

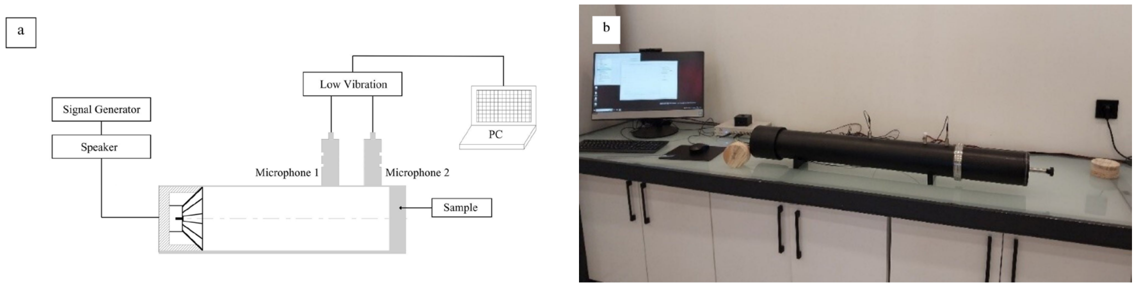


Fig. 6. a) Schematic diagram of the device used in the sound absorption test, b) impedance tube and test setup

The test samples were 99.5 mm in diameter; three pieces were prepared from each group and measurements were made. The sound absorption coefficients of the test samples prepared according to this standard were determined in frequency bands from 100 Hz to 1250 Hz. After the samples undergoing the test process were placed in the impedance tube, the sound absorption coefficients were determined.

The tube includes a built-in sound generator, an amplifier, and two 1/4" microphones (model: BSWA MP201, sensitivity 50 mV/Pa), spaced at a calibrated distance. Before testing, phase and amplitude calibration of the microphones was conducted using the BSWA CA114 calibrator (114 dB at 1 kHz), which is traceable to national metrology standards. Calibration was repeated before each test session to ensure accuracy.

This measurement approach is consistent with previous studies examining the acoustic behavior of timber-based panels using impedance tube setups (Proença *et al.*, 2024; Santos *et al.*, 2021).

9. Evaluation of data, statistical analysis

Statistical analyses of the experimental results were conducted using MSTAT-C statistical software, which is commonly used in agricultural and material sciences for analyzing replicated experimental data. Prior to inferential tests, the normality of data distributions was evaluated using the Shapiro–Wilk test, and the datasets were confirmed to exhibit normal distribution characteristics.

To evaluate the significance of observed variations, a one-way analysis of variance (ANOVA) was applied. Where significant differences were identified ($p < 0.05$), Duncan's Multiple Range Test (DMRT) was used as a post hoc analysis to determine statistically distinct groups and examine homogeneity among mean values. This methodological approach is consistent with previous studies that evaluated the acoustic and thermal performance of timber panels using factorial experimental designs (Santos *et al.*, 2021; Švajlenka *et al.*, 2020a; Švajlenka *et al.*, 2020b; Proença *et al.*, 2024).

Results and discussion

1. Air-dry density

The air-dry density values of the wood samples used in CLT panels before lamination were measured as 0.588 g/cm^3 for Scots pine, 0.746 g/cm^3 for sessile oak, and 0.435 g/cm^3 for Uludağ fir. These density differences are intrinsic to the wood species and significantly influence both the mechanical and thermal performance of CLT panels. As noted by Li *et al.* (2021), higher-density species such as sessile oak contribute positively to the structural rigidity of CLT, whereas lighter species such

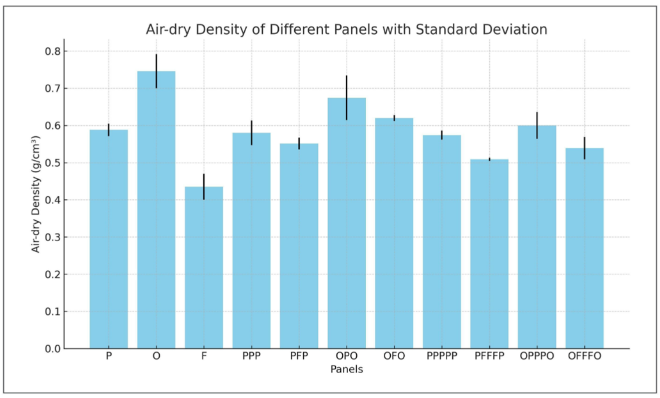


Fig. 7. Air-dry density values of CLTs

as Uludağ fir improve thermal insulation but reduce mechanical resistance.

When the density values in three- and five-layer CLT panels were examined, it was observed that the addition of low-density wood in the core layers led to a reduction in overall panel density. For example, the density of a three-layer OPO (Oak-Pine-Oak) panel was measured at 0.674 g/cm³, while a five-layer OPPPO (Oak-Pine-Pine-Pine-Oak) configuration, which included additional Uludağ fir layers, had a density of 0.600 g/cm³. This outcome confirms that a density layering strategy can be used to balance structural performance and thermal behavior.

These findings align with the results reported by Nakano *et al.* (2020), who emphasized the importance of density gradation in optimizing the performance of hybrid wood structures. Similarly, Proença *et al.* (2024) suggested that air-dry density plays a key role in influencing both dynamic mechanical response and insulation properties in engineered timber systems.

2. Moisture content

According to the experimental findings, equilibrium moisture content (EMC) varied significantly depending on the wood species used in the CLT panels. The highest EMC was observed in sessile oak control samples at 12.41%, while the lowest was found in Scots pine control samples at 10.08%, which aligns with the known hygroscopic behavior and density-related moisture affinity of these species (Schmidt *et al.*, 2019).

In three-layer CLT panels, the highest EMC was recorded in PFP configurations (outer Scots pine, inner Uludağ fir) at 8.87%, and the lowest in OPO panels (outer sessile oak, inner Scots pine) at 7.34%. Similarly, in five-layer CLT samples, PFFFP configurations yielded the highest EMC at 8.52%, whereas PPPPP panels had the lowest at 7.34%. These trends suggest that moisture buffering capacity differs not only between species but also depending on the lamination sequence and layering design (Nakano *et al.*, 2020).

Such variations in EMC are crucial as they influence the dimensional stability, bonding performance, and thermal behavior of the panels. These findings are consistent with those of Poblete *et al.* (2022), who emphasized the role of internal wood arrangement on the moisture equilibrium of hybrid wood-based composites. Similarly, Ma *et al.* (2021) reported that differences in EMC can directly affect the mechanical and thermal performance of timber structures, particularly under varying climate conditions.

These differences in equilibrium moisture values show that CLT panels exhibit different performances depending on the wood species, and this situation affects the mechanical strength and thermal properties (Ma *et al.*, 2021). The equilibrium moisture values of CLT panels are shown graphically in Fig. 8.

3. Thermal properties

This section contains the data obtained as a result of the experiments carried out to determine the heat conduction coefficients (W/m.K) and heat permeability coefficients (W/m².K) of cross-laminated timber panels.

4. Thermal conductivity

When analyzing the thermal conductivity coefficients (λ) of three-layer CLT panels, it was found that the OPO panel without perforation exhibited the highest thermal conductivity value at 0.137 W/m.K. In contrast, the PFP panel with 20% perforation had a significantly lower value of 0.102 W/m.K. This demonstrates that perforation leads to a reduction in thermal conductivity, with a decrease ranging between 1.10% and 6.54%, which aligns with findings in the literature suggesting that perforation increases air pockets within wood materials, thereby improving thermal performance (Li *et al.*, 2021; Nakano *et al.*, 2020).

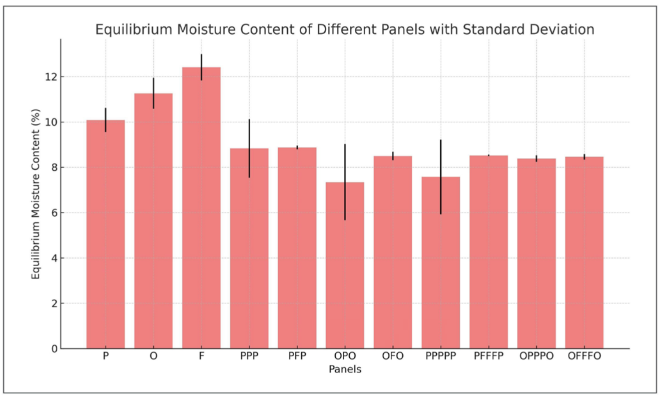
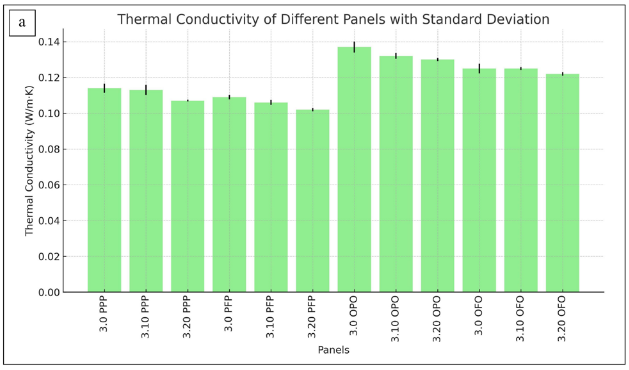


Fig. 8. Equilibrium moisture content of CLTs



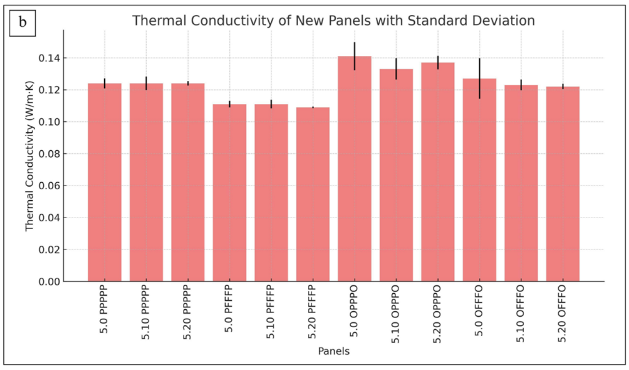


Fig. 9. a) Heat transfer coefficient values of three-layer CLT panels, b) heat transfer coefficient values of five-layer CLT panels

In five-layer configurations, the highest λ value was observed in the OPPPO (non-perforated) panel at 0.141 W/m·K, and the lowest in the PFFFP (20% perforated) panel at 0.109 W/m·K, reflecting a decrease between 0.01% and 3.93%. This trend aligns with previous findings that increased internal porosity via perforation enhances the thermal insulation properties of engineered wood panels (Zhao *et al.*, 2023).

Fig. 9 illustrates these variations, confirming that perforation is an effective method to improve the thermal insulation of CLT, particularly when energy efficiency is prioritized in building envelopes.

In three-layer CLT panels, the non-perforated OPO panel had the highest heat transfer coefficient of 0.137 W/m.K, while the 20% perforated PFP panel had the lowest value of 0.102 W/m.K. As the perforation ratio increased, decreases in heat transfer were observed, and these decreases ranged between 1.10% and 6.54% in perforated panels.

In five-layer panels, the non-perforated OPPPO panel had the highest heat transfer value of 0.141 W/m.K, while the 20% perforated PFFFP panel had the lowest heat transfer value of 0.109 W/m.K. In general, a decrease in heat transfer was recorded between 0.01% and 3.93% in perforated panels.

Three-layer panels demonstrated significantly lower heat conduction than five-layer ones, due to the smaller number of lamination interfaces and reduced thermal mass. The literature supports the finding that additional layers increase internal density and may impede airflow, thereby influencing thermal resistance (Liu *et al.*, 2018).

According to the variance analysis, the effect of the number of layers and perforation rates on heat conduction was found to be statistically significant, and homogeneity groups were determined by the Duncan test.

As shown in Table 3, the heat conduction coefficient of three-layer CLT panels (0.118 W/m.K) was found to be lower than that of five-layer panels (0.124 W/m.K),

Table 3. Homogeneity groups of heat transfer coefficient values according to the number of layers

	CLT panels		
Layers	**N**	$\bar{X}$ **(W/m.K)**	**HG**
3 layers	36	0.118	B
5 layers	36	0.124	A

Table 4. Homogeneous groups of thermal conductivity coefficients based on perforation percentages

	CLT panels		
Perforation ratio	**N**	$\bar{X}$ **(W/m.K)**	**HG**
0% (Control)	24	0.124	A
10%	24	0.121	AB
20%	24	0.119	B

and this difference is statistically significant. This result shows that increasing the number of layers leads to a slight increase in heat conduction by increasing the thermal resistance capacity inside the material. It is also stated in the literature that panels with more layers show different thermal properties due to the density in the internal structure and the effect on air flow (Liu *et al.*, 2018). Homogeneity groups of heat conduction coefficients according to perforation percentages are given in Table 4.

As shown in Table 4, statistically significant differences were observed in the thermal conductivity coefficient (λ) of CLT panels depending on the perforation rates. CLT panels with 20% perforation had the lowest thermal conductivity coefficient of 0.119 W/m.K, showing a significant improvement compared to the control group (0% perforation).

These findings are consistent with those of Shan *et al.* (2023) and Peng *et al.* (2018), who showed that air-filled voids reduce thermal conductivity by increasing internal resistance to heat flow. Thus, perforation emerges as a practical design strategy to enhance thermal insulation in CLT elements.

In summary, both perforation and selection of the number of layers are effective strategies for improving the thermal efficiency of CLT panels. Their combined effects lead to better insulation, contributing to sustainable and energy-efficient building solutions.

5. Thermal transmittance

Thermal transmittance coefficient (U-value) results demonstrated clear variation based on the number of layers, perforation rates, and the species of wood used in the outer and intermediate layers of the CLT panels. These variations are visually represented in Fig. 10.

In the experiments conducted on three-layer CLT panels, it was observed that the heat conductivity coefficient of the OPO configuration with no perforation in the interlayer was higher than for the other CLT panels, reaching 2.757 W/m².K. In contrast, the PFP configuration with 20% perforation in the interlayer had a lower heat conductivity coefficient of 2.022 W/m².K, which represents good performance. A similar result was observed for five-layer CLT panels: 1.705 W/m².K was recorded for the non-perforated OPPPO configuration, and 1.297 W/m².K for PFFFP with 20% perforation in the intermediate layers.

These results suggest that perforation significantly reduces the thermal transmittance by enhancing internal air cavity formation, thereby increasing insulation performance. Statistical analysis confirmed that both the number of layers and the perforation percentage had significant effects on the U-value ($p < 0.05$). Duncan's multiple range test was used to identify statistically homogeneous groups.

The homogeneity groups of heat conductivity coefficient (U) averages depending on the number of layers and perforation rates of CLT panels are given in Table 5 and Table 6, respectively.

As shown in Table 5, the heat transmittance coefficient (U) of five-layer CLT boards was lower than that of three-layer boards, at 1.473 W/m².K, and this difference was found to be statistically significant. The lower heat transmittance of five-layer boards indicates that increasing the number of layers improves the thermal performance of the material. Similarly, there are findings in the literature that wooden structures with more layers increase energy efficiency by reducing heat conduction (Peng *et al.*, 2018) This result reveals that the thermal resistance mechanisms in the internal structure become more effective as the number of layers increases.

The results obtained for heat transmission coefficients in relation to perforation rates show that perforation has a direct effect on the thermal performance of CLT panels. As seen in Table 6, the heat transmission coefficient (U) in CLT panels with 20% perforation has the lowest value (1.868 W/m².K). This indicates that perforation reduces the heat conduction of the material, since as the perforation rate increases, the air gaps increase, which increases the heat conduction

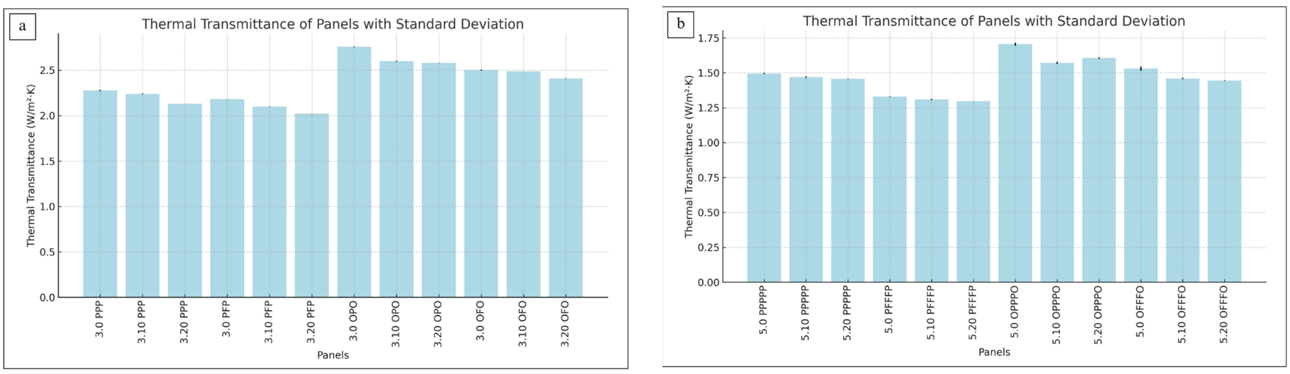


Fig. 10. Heat transmittance coefficient: a) three-layer CLT panels, b) five-layer CLT panels

Table 5. Thermal transmittance homogeneity groups based on the number of layers

	CLT panels		
Layers	**N**	**$\bar{X}$ (W/m².K)**	**HG**
3 layers	36	2.356	A
5 layers	36	1.473	B

Table 6. Thermal transmittance homogeneity groups based on perforation percentages

	CLT panels		
Perforation ratio	**N**	**$\bar{X}$ (W/m².K)**	**HG**
0% (Control)	24	1.972	A
10%	24	1.904	B
20%	24	1.868	B

path and improves the thermal performance (Shan *et al.*, 2023). Increasing perforation rates cause the air pockets within the panels to expand, thus decreasing the thermal conductivity. This situation was observed especially at higher perforation rates. The fact that CLT panels with 20% perforation have a lower heat transmission coefficient indicates that perforation increases the thermal resistance capacity of the material. Similar results in the literature show that perforated building materials provide improvement in thermal insulation performance. Perforations prevent heat transfer by creating air pockets, which increases the thermal resistance of the material.

Other studies also support the effect of perforation on thermal conductivity. For example, Gu and Zink-Sharp (2005) explained how perforation reduces heat transfer and how air gaps in the material prevent this process. In addition, studies on the thermal conductivity of various wood species show that changes in the internal structure of the material directly affect the heat transfer process (Song *et al.*, 2023).

These findings highlight the potential of perforated CLT panels in improving building energy performance, particularly in applications requiring optimized insulation, such as in passive houses and energy-efficient retrofits.

6. Sound absorption

Graphs of sound absorption coefficients (α) of 3-layer and 5-layer CLT panels, determined by the impedance tube method according to ASTM E 1050-08, are shown in Fig. 11.

It is seen in Fig. 11 and Fig. 12 that the sound absorption performance of CLT panels varies significantly depending on the frequency. A significant increase was observed in the sound absorption coefficients of perforated panels, especially at medium and high sound frequencies. Perforated panels such as 3.10 PFP and 3.20 PPP exhibited the highest sound

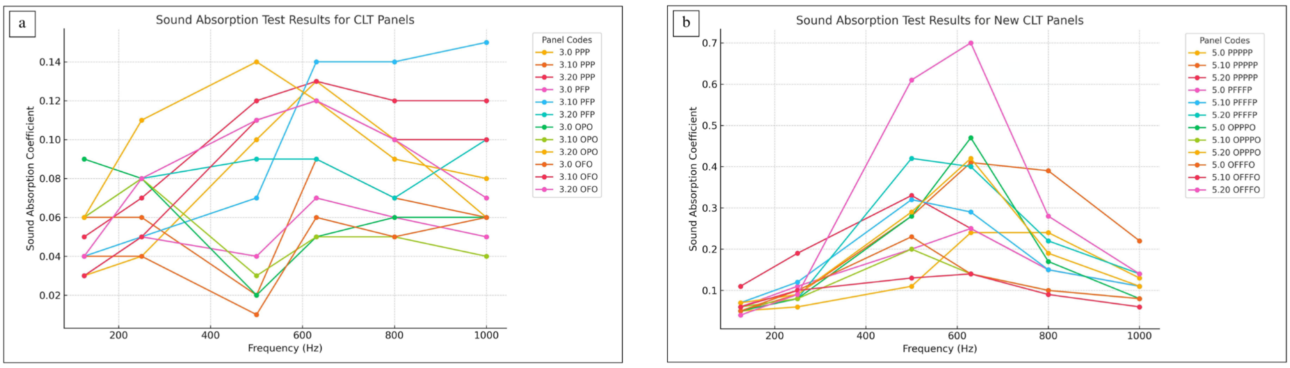


Fig. 11. Sound absorption test results for CLT panels: a) 3-layer CLT panels, b) 5-layer CLT panels

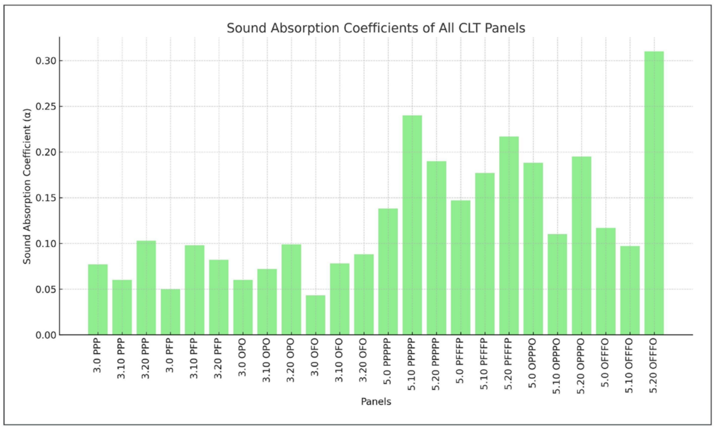


Fig. 12. Average values of sound absorption coefficients of three- and five-layer CLT panels

absorption performance in general. The 5.20 OFFFO panel achieved the highest performance at frequencies of 500 Hz and 630 Hz, and similarly, the 5.20 PPPPP panel exhibited high sound absorption coefficients at these frequencies. These findings support the assumption that perforation creates air pockets, allowing sound to disperse better within the material, thus improving acoustic performance. Other studies also confirm that increasing the perforation rate provides improvement in sound absorption performance (Song *et al.*, 2016).

As seen in Table 7, the sound absorption coefficient of three-layer CLT panels (α = 0.076) is lower than that of five-layer CLT panels, and this difference was found to be statistically significant. This shows that CLT panels with more layers have an increased sound absorption capacity. Similar studies in the literature emphasize that acoustic performance improves with an increase in the number of layers (Di Bella *et al.*, 2017).

The results in Table 8 reveal that perforation ratios have a significant effect on the sound absorption coefficient of CLT panels. It was found that CLT panels with 0% perforation exhibited the lowest performance, with a sound absorption coefficient (α) of 0.103, while panels with 10% perforation achieved slightly higher performance with a sound absorption coefficient of 0.116. These differences are statistically significant, and an overall improvement in sound absorption performance is observed as the perforation ratio increases.

These findings confirm the role of perforation in improving the acoustic properties of CLT panels. Increasing the perforation rate contributes to the absorption of sound by creating air gaps within the material and therefore increases the acoustic performance. Similarly, this increase in the sound absorption coefficient of CLT panels with increasing perforation rates can be attributed to the changes in the microstructure of the material. Air pockets allow sound waves to disperse more within the material and thus allow a more effective absorption process (Bettarello *et al.*, 2021; Vardaxis *et al.*, 2022). As a result, perforation in CLT panels is seen to be an effective method to optimize sound absorption performance. This supports the preference for perforated CLT

Table 7. Homogeneous groups of sound absorption coefficients based on the number of layers

	CLT panels		
Layers	**N**	**$\bar{X}$ (α)**	**HG**
3 layers	216	0.076	B
5 layers	216	0.177	A

Table 8. Homogeneous groups of sound absorption coefficients based on perforation percentages

	CLT panels		
Perforation ratio	**N**	**$\bar{X}$ (α)**	**HG**
0% (Control)	144	0.103	C
10%	144	0.116	B
20%	144	0.160	A

Table 9. Homogeneous groups of sound absorption coefficients based on frequency ratios

CLT panels			
Frekans (Hz)	**N**	**$\bar{X}$ (α)**	**HG**
125	72	0.055	F
250	72	0.083	E
500	72	0.183	B
630	72	0.208	A
800	72	0.134	C
1000	72	0.096	D

Table 10. Homogeneous groups of sound absorption coefficients based on the interaction between layer number and perforation

CLT panels				
Layers	**Perforation ratio**	**N**	**$\bar{X}$ (α)**	**HG**
3	0% (Control)	72	0.058	F
	10%	72	0.077	E
	20%	72	0.093	D
5	0% (Control)	72	0.148	C
	10%	72	0.156	B
	20%	72	0.228	A

panels especially in buildings where acoustic performance needs to be improved.

Analysis of the sound absorption coefficients in Table 9 shows that the values in the frequency ranges of 500 Hz, 630 Hz and 800 Hz are significantly higher than for other frequencies. In particular, the highest sound absorption coefficient (0.208) was obtained at a frequency of 630 Hz. This reveals that sounds at medium frequencies are absorbed more effectively by CLT panels. Similarly, relatively high values such as 0.183 at 500 Hz and 0.134 at 800 Hz were obtained, indicating that these frequency ranges are important in sound absorption performance. Studies in the literature reveal that the sound absorption performance of materials is generally higher at medium frequencies and that these frequencies are critical for acoustic comfort (Kang *et al.*, 2023).

On the other hand, it was observed that the sound absorption coefficient was lower at low and high frequencies such as 125 Hz and 1000 Hz. This shows that the material has limited ability to absorb low and very high frequency sounds. In general, the higher performance at medium frequencies indicates that these frequencies are more suitable for optimizing the acoustic performance of CLT panels.

As seen in Table 10, the number of layers and the perforation rate have a significant effect on the sound absorption coefficient of CLT panels. Five-layered and 20% perforated CLT panels exhibited the best performance, with the highest sound absorption coefficient (α = 0.228). This finding shows that increasing the number of layers and increasing the perforation rate improves the sound absorption performance by increasing the air pockets in the material. On the other hand, three-layered and non-perforated (control group) CLT panels had the lowest sound absorption coefficient (α = 0.058). This indicates that less layered structures and non-perforated panels are less effective at sound insulation. These findings indicate that increasing the number of layers and optimizing perforation rates in CLT panels is an effective strategy to improve acoustic performance.

As shown in Table 11, when the interaction between the number of layers and sound frequency was examined, the highest sound absorption coefficient of 0.321 (α) was obtained at the sound frequency of 630 Hz for five-layer CLT panels. This shows that the acoustic performance of five-layer panels is better, especially in the mid-frequency range. It was observed that sound waves are absorbed more effectively at this frequency and therefore the sound absorption performance in the interior increases. Five-layer CLT panels have increased acoustic resistance due to their more layered structures, and

Table 11. Homogeneous groups of sound absorption coefficients based on the interaction between layer numbers and sound frequency

Layers	Frekans (Hz)	N	$\bar{X}$ (α)	HG
3	125	36	0.049	J
	250	36	0.067	H
	500	36	0.082	F
	630	36	0.095	E
	800	36	0.084	F
	1000	36	0.078	G
5	125	36	0.061	I
	250	36	0.099	E
	500	36	0.283	B
	630	36	0.321	A
	800	36	0.184	C
	1000	36	0.114	D

Table 12. Homogeneous groups of sound absorption coefficients based on the interaction between perforation and sound frequency

Perforation ratio	Frekans (Hz)	N	$\bar{X}$ (α)	HG
0%	125	24	0.050	L
	250	24	0.070	J
	500	24	0.124	G
	630	24	0.176	C
	800	24	0.116	H
	1000	24	0.079	J
10%	125	24	0.054	K
	250	24	0.079	J
	500	24	0.160	D
	630	24	0.169	C
	800	24	0.136	F
	1000	24	0.101	I
20%	125	24	0.061	K
	250	24	0.100	I
	500	24	0.264	B
	630	24	0.278	A
	800	24	0.150	E
	1000	24	0.109	H

optimize the absorption of sounds at mid-frequencies. On the other hand, the lowest sound absorption coefficient (α) of 0.049 was determined at a sound frequency of 125 Hz for three-layer CLT panels. This shows that three-layer panels exhibit poorer sound absorption performance at low sound frequencies. It is understood that at low frequencies, the absorption of sound waves is less effective and therefore panels perform less well in providing indoor comfort. Similar studies in the literature emphasize that the acoustic performance of thicker and multi-layered CLT panels is superior especially at medium and high frequencies.

As seen in Table 12, it was observed that there was a significant increase in the sound absorption coefficient (α) of CLT panels as the perforation ratio increased. In particular, CLT panels with a perforation ratio of 20% attained the highest sound absorption coefficient value (α = 0.278) at a frequency of 630 Hz. This finding is consistent with reports in the literature that perforation increases acoustic performance.

It has been stated in the literature that wood materials improve sound absorption performance and allow sound to spread more within the material (Logawa, 2017; Kang *et al.*, 2024). The lowest sound absorption coefficient value (α = 0.050) was recorded at a frequency of 125 Hz for panels without perforation. This can be attributed to the fact that low frequencies carry less energy and the effect of perforation is limited at these frequencies. CLT panels with high perforation ratios create air pockets, allowing more sound to be absorbed. In addition, the effect of perforation becomes evident at medium frequencies such as 500 Hz and 630 Hz, and sound absorption performance increases significantly at these frequencies.

These findings support the practical application of perforated CLT panels in buildings requiring enhanced acoustic performance, such as schools, offices, and residential complexes located in high-noise environments.

Conclusions

This study has examined the air-dry density, moisture content, and thermal and acoustic properties of cross-laminated timber (CLT) panels with varying wood species, layer configurations, and perforation ratios.

The findings support the initial hypotheses: increased perforation ratios led to a measurable reduction in thermal conductivity and an improvement in sound absorption, particularly in mid-frequency ranges. Additionally, lower-density wood species such as Uludağ fir contributed to enhanced thermal insulation, while high-density woods like sessile oak improved mechanical integrity but resulted in higher thermal conductivity.

Perforation proved effective in forming internal air pockets, thereby increasing thermal resistance and reducing heat transfer, and confirming its role in improving energy efficiency. Similarly, perforated panels demonstrated superior acoustic performance, especially in five-layer configurations with 20% perforation, indicating their potential application in buildings where noise control is critical.

These results have both local and global implications. Locally, they provide a strategy for improving the sustainability of building envelopes in climates similar to Turkey's. Globally, the findings contribute to the advancement of eco-efficient wood-based materials in construction, aligning with international goals for reducing energy consumption and enhancing indoor environmental quality.

In conclusion, optimizing perforation geometry and layer composition in CLT panels can significantly enhance both thermal and acoustic performance. These improvements make perforated CLT a promising material for sustainable architectural applications where energy efficiency and acoustic comfort are key design priorities.

Conflict of interest

The author(s) declare(s) that there is no conflict of interest concerning the publication of this article.

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