 DOI: 10.22616/RRD.31.2025.049

EVALUATING THERMAL PROPERTIES OF NORWAY SPRUCE CROSS-LAMINATED TIMBER PANELS AT DIFFERENT WOOD MOISTURE CONTENTS

***Edvīns Grants[1], Uldis Gross[2], Viktorija Strausiņa[2]**
[1]Forest and Wood Products Research and Development Institute (MeKA), Latvia
[2]Latvia University of Life Sciences and Technologies (LBTU), Latvia
*Corresponding author's email: edvins.grants@e-koks.lv

Abstract
This study explores the thermal conductivity of cross-laminated timber made from Norway spruce (*Picea abies* L.), emphasizing the impact of varying wood moisture content, density, and temperature. A comprehensive set of eighty specimens was prepared, grouped into four clusters of twenty specimens each, categorized by average density to ensure consistent representation. Measurements were conducted at equilibrium temperatures 10 °C, 20 °C and 23 °C (temperature difference 10 °C) using Heat Flow Meter HFM 436/3. The study identified a quadratic relationship between thermal conductivity and bulk density, with conductivity increasing non-linearly. Dispersion and regression analysis comparing results to ISO 10456 standard showed experimental values were consistently lower, highlighting potential overestimation in standardized data. Density-dependent trends at 23 °C demonstrated better alignment, but deviation from historical models for solid wood thermal conductivity dependence to wood density and moisture content (e.g., MacLean, Tenwolde) emphasized the need for updated, cross-laminated timber specific data. This research enhances energy efficiency modelling for building with cross-laminated timber products in the external envelope of the building by providing more precise conductivity values. The findings emphasize equilibrium moisture content of wood dependence of climatic conditions and its impact on energy performance of mass timber structures. The findings support updates to thermal performance standards. Addressing variable conditions, this work lays the groundwork for accurate modelling of specific cross-laminated timber product behaviour in real-world applications.
Keywords: cross-laminated timber (CLT), thermal conductivity, Norway spruce, *Picea abies* L., moisture content.

Introduction

Cross-laminated timber (CLT) is a known construction product that has gained significant attention in recent years in the context of sustainable building. The thermal properties of CLT are crucial factor influencing the energy efficiency of buildings, especially in external envelope applications. While the thermal conductivity of natural solid wood depends on various factors, including wood species, density, porosity, anisotropy and moisture content, these factors may manifest differently in CLT due to its specific structure. Previous studies (MacLean, 1941; Wilkes, 1988; Tenwolde et al., 1988) give solid background for prediction solid wood thermal performance, however, standards such as ISO 10456 (International Organization for Standardization, 2007) and ISO 10077-2 (International Organization for Standardization, 2017) give only partial guidance for wood and wood-based products, CLT as material category is not even mentioned. Other product assessment guidance documents such as EAD 130005-00-0304 (European Organisation for Technical Assessment, 2015) recommend to use design values as declared for solid wood materials, when no testing is done. Recent study suggested (Flexeder et al., 2021) that CLT panels might have different thermal conductivity values as tabulated values in standards.

The service conditions of buildings significantly impact the equilibrium moisture content (EMC) of solid wood materials, which can vary substantially throughout the year, dynamically influencing the energy efficiency indicators of a building. Earlier studies (Hunt et al., 2008; Avramidis & Liadis, 2005) have shown that moisture redistribution within wood can alter its heat transfer properties, necessitating careful consideration of moisture dynamics in thermal conductivity models. The work of Flexeder et al. (2021) further highlights the need for long-term monitoring of CLT structures to evaluate their hygrothermal performance under real-world conditions.

The HFM 436/3 Lambda (NETZSCH-Gerätebau GmbH., n.d.) heat flow meter is widely used in research for measuring thermal conductivity, contributing to data accuracy and comparability across different studies. The standards serve as benchmarks for evaluating CLT's thermal performance under varied environmental criteria.

Therefore, it is essential to determine precise parameters characterizing the changes in CLT thermal conductivity under different moisture and thermal conditions. This study analyses the thermal conductivity of Norway spruce (*Picea abies* L.) CLT panels at various wood moisture contents to understand how moisture and density affect the thermal behaviour of the material. The aim of this study is to verify whether a statistically significant and practically relevant dependence exists between the thermal conductivity of industrial cross-laminated timber panels and their wood-moisture content and bulk density under typical service temperatures.

The study employs an experimental approach, conducting thermal conductivity measurements at different equilibrium moisture levels and temperatures. The methodology follows prior research on thermal conductivity models (Hunt et al., 2008) and compares empirical findings with existing standardized values and computational predictions. By integrating past empirical data (MacLean, 1941) with modern modelling techniques and real-world monitoring insights from Flexeder et al. (2021), this research aims to refine thermal property predictions for CLT. The study's findings can be valuable for designers and building regulation developers seeking to improve the energy efficiency modelling of mass timber constructions and enhance the accuracy of existing standards. The novelty of the work lies in providing the first coherent experimental dataset for CLT across the range of 10 % to 21 % equilibrium wood moisture content and demonstrating how the measured values deviate from ISO 10456 reference data.

Materials and Methods

This study investigated the thermal conductivity of Cross Laminated Timber (CLT) panels under different conditioning regimes. The specimens were prepared based on the technical constraints of Heat Flow Meter (HFM 436/3 Lambda), which have fixed sample chamber size. Three-layer CLT panel cutoffs were selected randomly. Each panel was approximately 60 mm thick, composed of 20 mm thick and 120 mm wide Norway spruce (*Picea abies* L.) lamellas, bonded with polyurethane (PU) adhesive. The adhesive layer thickness was approximately 0.1 mm. The lamellas were manufactured from strength-graded sawn timber according to EN 14081-1 (European Committee for Standardization, 2020), with a characteristic strength class of C24 according to EN 338 (European Committee for Standardization, 2016a). Square-shaped specimens with side length of 290 mm were cut, yielding a total of 80 samples.

To analyse the effect of moisture content on thermal conductivity, four conditioning regimes were applied:

1. **Conditioning regime 1** – Temperature 18 °C / Relative air humidity (RH) 90 %: Target Equilibrium Moisture Content of wood (EMC) ~ 21 %;
2. **Conditioning regime 2** – Oven dried samples at temperature 103 °C till constant weight (European Committee for Standardization, 2002a);
3. **Conditioning regime 3** – Temperature 23 °C / RH 50 %: EMC ~ 10 % (ISO 10456 reference conditions);
4. **Conditioning regime 4** – Temperature 20°C / RH 65 %: EMC ~ 12 % (Service Class 1 reference conditions according EN 1995-1-1 (European Committee for Standardization, 2005), also reference conditions for tabulated design thermal conductivity (λ) values of solid wood in ISO 10456).

Wood moisture content (MC) measurements were performed using the Brookhuis FMD v5.0 wood moisture meter equipped with Teflon-coated electrode needles, following the recommendations of EN 13183-2 (European Committee for Standardization, 2002b). Measurements were taken from both sided of each sample. The electrode needles were oriented parallel to the wood grain and inserted at the centre of the specimen, approximately 30 mm deep, as suggested in EAD 130005-00-0304. The Second group of specimens (oven-dried) did not undergo moisture measurements; instead, they were immediately wrapped in LDPE plastic film and transferred to the thermal conductivity test setup.

Thermal conductivity measurements were conducted using the HFM 436/3 Lambda apparatus according to EN 12667 standard method (European Committee for Standardization, 2001). Apart from varying the plate-equilibrium temperatures to study their influence on CLT, all operational parameters followed the standard procedure (NETZSCH-Gerätebau GmbH., n.d.). Each specimen was measured at three equilibrium temperatures: 10 °C, 20 °C and 23 °C with a temperature gradient (ΔT) of 10 °C between the hot and cold plates. Since the specimen dimensions exceeded the measurement area, perimeter insulation was not applied. To ensure proper contact with the measurement plates, the sample surfaces were lightly sanded.

Data from 72 successfully conditioned specimens were analysed. Microsoft Excel was used for data compilation, while statistical analysis was performed using R 4.4.3 in RStudio 2024.12.1+563. The analysis included correlation and regression modelling, as well as ANOVA testing to assess the influence of Moisture content (MC), density (ρ) and equilibrium temperature on CLT thermal conductivity. Experimental results were compared with ISO 10456 and ISO 10077-2 reference values. Characteristic density values were calculated according EN 14358 (European Committee for Standardization, 2016b), and thermal conductivity reference values were derived using ISO 10456.

Results and Discussion

To evaluate the relationship between density and thermal conductivity, regression analysis was performed for each conditioning regime and equilibrium temperature. The results are summarized in Table 1, which presents the regression equations, correlation coefficients (r), coefficients of determination (R^2), average measured thermal conductivity ($\bar{\lambda}$), 90%-percentile of measured data according ISO 10456 (λ_D), measured average densities ($\bar{\rho}$), 5%-percentile values of measured sample densities according to EN 14358 (ρ_k), measured average CLT moisture content (MC) and corresponding standard deviations (s).

These values illustrate how moisture content influences the strength of the density and thermal conductivity relationship, with higher humidity levels generally leading to stronger correlations. Stronger correlation (r > 0.75) was observed in conditioning regimes with higher relative moisture (RH = 90 %), confirming that moisture amplifies density effect on thermal conductivity. R^2 values varied between 0.13 (oven-dried group of samples) and 0.77 (samples conditioned at high RH), suggesting that moisture increases the predictability of density effects. Conditioning regimes significantly affected thermal conductivity, with the highest thermal conductivity measurement values obtained from samples conditioned at environment with high RH.

Table 1

Regression Analysis Summary

Cond. Regime	*Regression Equation at Equilibrium temperature*	*Correlation coefficient, r*	*Coefficient of determination, R^2*	*Measured average thermal conductivity, $\bar{\lambda}$ (W/m·K)*	*Declared thermal conductivity, λ_D (W/m·K)*	*Standard deviation, s*	*Measured average density, $\bar{\rho}$ (kg/m^3)*	*Calculated characteristic density, ρ_k(kg/m^3)*	*Standard deviation, s*	*Measured average wood moisture content, MC (%)*	*Standard deviation, s (%)*
1	λ_{10} = 0.00013*ρ + 0.0478	0.80	0.64	0.111	0.132	0.011	498	376	66.9	18	4.7
1	λ_{20} = 0.00015*ρ + 0.0389	0.88	0.77	0.113	0.136	0.011	498	376	66.9	18	4.7
1	λ_{23} = 0.00013*ρ + 0.0451	0.86	0.73	0.108	0.128	0.010	498	376	66.9	18	4.7
2	λ_{10} = 0.00011*ρ + 0.0390	0.40	0.16	0.083	0.090	0.004	411	374	20.5	NA	NA
2	λ_{20} = 0.0001034*ρ + 0.0420	0.36	0.13	0.084	0.092	0.004	411	374	20.5	NA	NA
2	λ_{23} = 0.00009383*ρ + 0.0450	0.34	0.12	0.084	0.091	0.004	411	374	20.5	NA	NA
3	λ_{10} = 0.00015*ρ + 0.0311	0.66	0.43	0.099	0.107	0.005	451	411	22.6	11	0.6
3	λ_{20} = 0.00016*ρ + 0.0279	0.63	0.40	0.100	0.109	0.005	451	411	22.6	11	0.6
3	λ_{23} = 0.0001979*ρ + 0.0101	0.82	0.67	0.099	0.109	0.005	451	411	22.6	11	0.6
4	λ_{10} = 0.00017*ρ + 0.0262	0.69	0.48	0.102	0.103	0.004	455	414	22.8	12	0.5
4	λ_{20} = 0.00016*ρ + 0.0323	0.66	0.44	0.103	0.111	0.004	455	414	22.8	12	0.5
4	λ_{23} = 0.00016*ρ + 0.0275	0.76	0.57	0.103	0.110	0.004	455	414	22.8	12	0.5

The highest slope (~ 0.00017) was observed with samples conditioned in 20 °C / 65 % RH, indicating that in moderate humidity, defined as limit value for Service Class 1 (SC1) environmental conditions in Eurocode 5, density exerts the greatest effect. This highlights the importance of classifying environmental exposure classes correctly when modelling thermal performance in buildings using CLT construction products. Moisture levels not only shift the mean conductivity values but also affect the sensitivity of conductivity to density variations, thereby impacting predictive modelling.

Furthermore, comparison of regression intercepts across conditioning regimes revealed how base thermal conductivity changes independently of density. Higher intercepts in high relative humidity conditions suggest intrinsic conductivity increase due to bound water content in the wood structure. This aligns with previously observed effects in solid wood studies and reinforces the necessity for CLT-specific datasets.

Figure 1

Thermal Conductivity Distribution at 10 °C, 20 °C and 23 °C Equilibrium Temperatures for Conditioning Regime 4

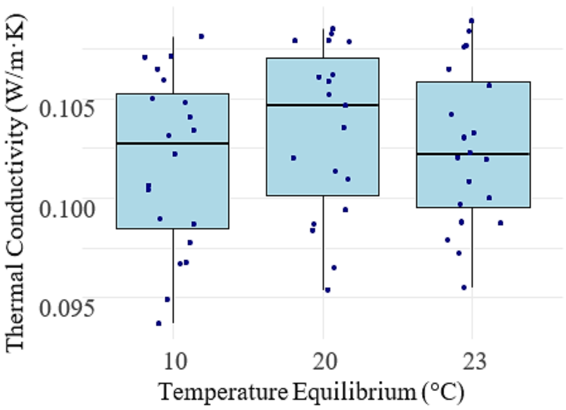
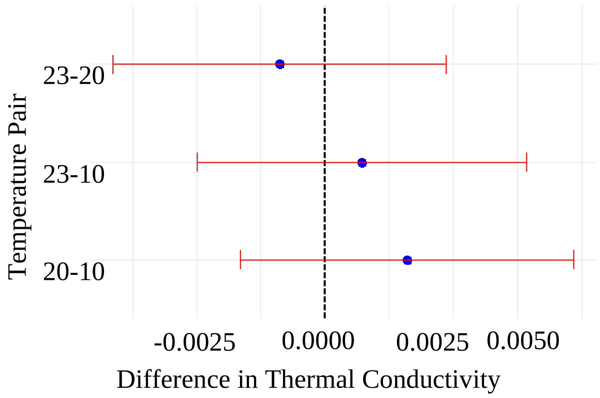


Table 1 provides an overview of how environmental conditions alter the role of density in thermal conductivity predictions, offering insight into potential modifications for CLT-based structures of building external envelope, playing role as part of thermal insulation and energy performance modelling.

To examine the effect of thermal equilibrium temperature on CLT thermal conductivity, boxplots were generated for each conditioning regime, and Tukey's Honestly Significant Difference (HSD) test was conducted. The results provide insights into whether temperature variations within the studied range significantly impact heat transfer properties.

Figure 2

Tukey's (HSD) test for Temperature Equilibrium Differences at Conditioning Regime 4



A representative boxplot 'Figure 1' shows the thermal conductivity distribution at 10 °C, 20 °C, and 23 °C equilibrium temperatures, highlighting differences across conditioning regimes. The Tukey HSD results 'Figure 2' illustrate statistical groupings, showing whether conductivity changes significantly with temperature.

The data suggest that while temperature has a secondary role compared to moisture and density, it can introduce measurable differences, particularly in samples with elevated MC. This implies that simplified models assuming constant λ across narrow temperature bands may overlook relevant variability in real-world application. These findings (Table 2) indicate that thermal equilibrium temperatures do not have a statistically significant impact on CLT thermal conductivity, suggesting that other parameters such as moisture and density are the primary influencing factors.

In all conditioning regimes, mean conductivity values remain stable across the tested equilibrium temperatures, as confirmed by Tukey's Honestly Significant Difference (HSD) test. This stability implies that within typical indoor climate conditions, temperature variation alone does not introduce meaningful fluctuations in CLT thermal performance.

Table 2

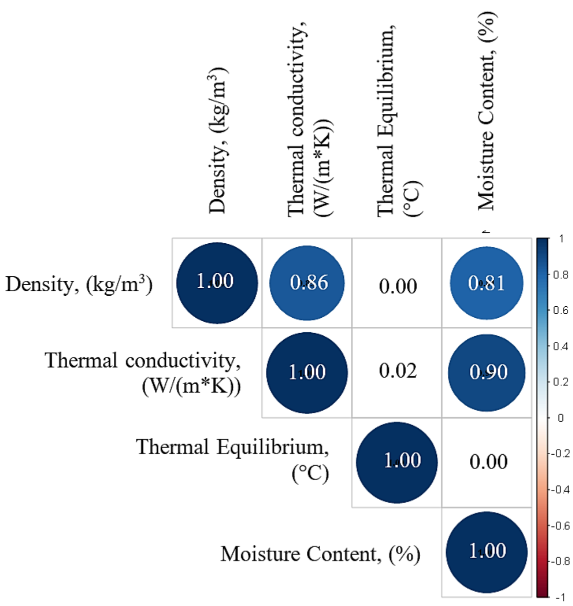
Dispersion Analysis Summary

Conditioning Regime	***Measured average thermal conductivity at 10 °C thermal equilibrium, $\overline{\lambda_{10°C}}$ (W/m·K)***	***Measured average thermal conductivity at 20 °C thermal equilibrium, $\overline{\lambda_{20°C}}$ (W/m·K)***	***Measured average thermal conductivity at 23 °C thermal equilibrium, $\overline{\lambda_{23°C}}$ (W/m·K)***	***Tukey significance ($p < 0.05$)***
1	0.111	0.113	0.108	No significant difference
2	0.083	0.084	0.084	No significant difference
3	0.099	0.100	0.099	No significant difference
4	0.102	0.103	0.103	No significant difference

To evaluate the accuracy of standardized thermal conductivity values, the experimentally measured data was compared against ISO 10456 reference values. The scatter plot 'Figure 3' illustrates deviations between measured values and standard predictions, highlighting systematic discrepancies across different density ranges.

Figure 3

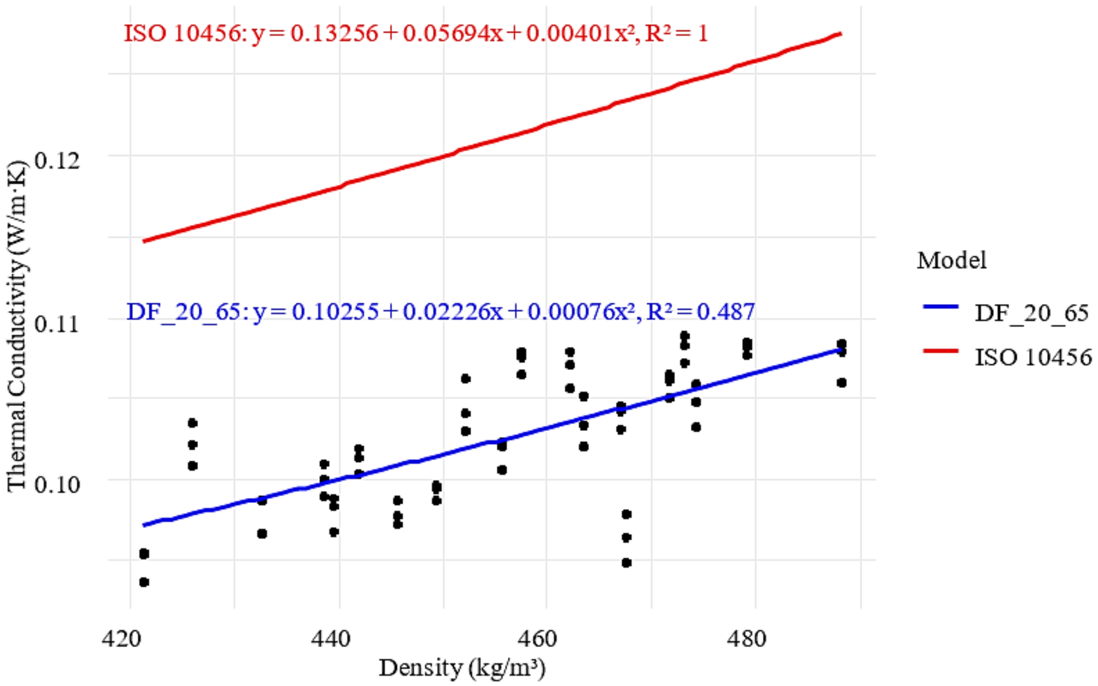
Thermal Conductivity Influencing Key Factor Correlation Matrix



In particular, the trend of overestimation becomes more evident at lower densities, where measured values deviate furthest from the ISO reference line.
The ISO 10456 model consistently overestimates thermal conductivity values across the tested density range. The experimental data follows a quadratic regression trend, deviating from the similar ISO 10456 assumptions. This discrepancy suggests that ISO models may not fully capture other factors (e.g. knots, splits, resin pockets, fissures between laminations, adhesive dependant effects, not evaluated in this paper) and the moisture-dependent variations in CLT thermal conductivity.

To identify key factors influencing thermal conductivity measured during experiment, a correlation matrix was generated ‘Figure 4’.
The correlation analysis confirms that:
- Density strongly correlates with thermal conductivity (r = 0.85);
- Moisture content exhibits a high correlation with thermal conductivity (r = 0.90), reinforcing its significance as contributing factor;
- Equilibrium temperature has a negligible effect ($r \approx 0.02$), further validating previous findings that temperature variations within the tested range have minimal impact.

Figure 4
Comparison of Theoretical ISO 10456 Model with Experimental Data Obtained from Samples Conditioned at Reference Conditions 20 °C and 65 % RH



To improve predictive accuracy, multiple regression models were tested using density and moisture content as key independent variables. The best-performing models are summarized in Table 3.

Table 3
Multifactor Regression Analysis Summary

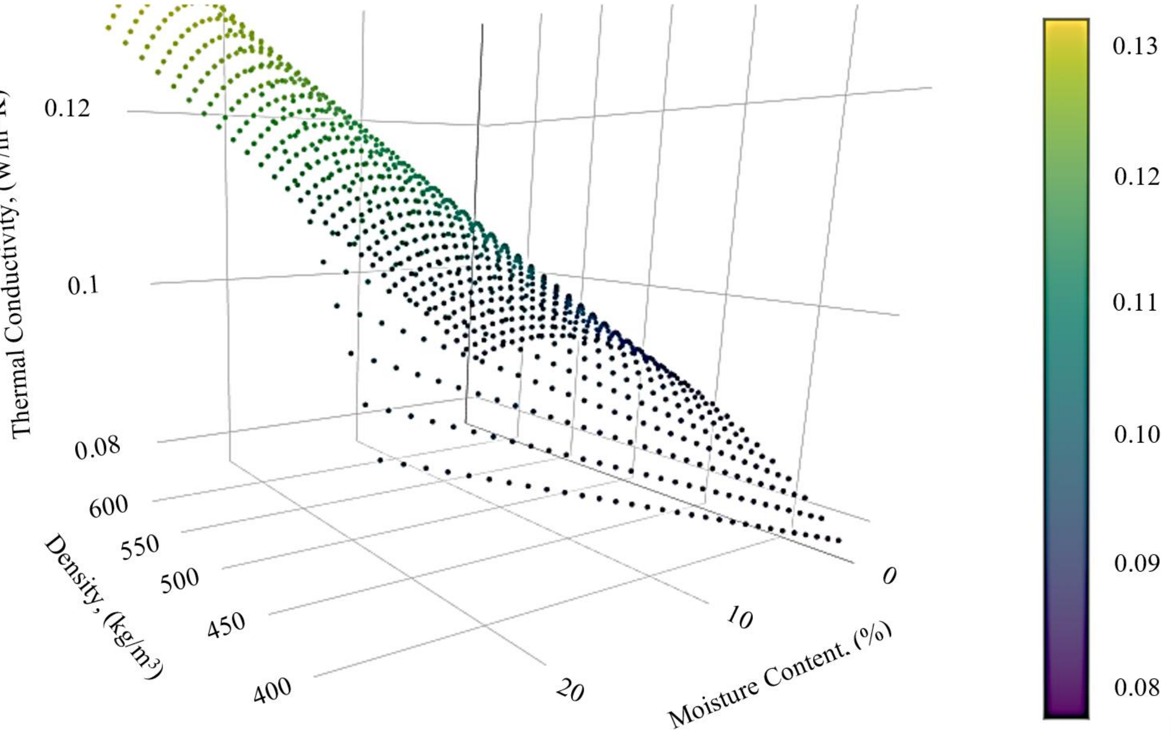
Model	***Regression Equation***	R^2
Without MC	$\lambda = 0.137\rho^2 + 0.098$	0.78
With MC	$\lambda = 0.066\rho^2 + 0.089 - 0.022MC$	0.87
With MC interaction	$\lambda = 0.029\rho^2 + 0.088 - 0.034MC + 0.102\rho\, MC$	0.88

The model incorporating moisture interaction effects provided the highest accuracy ($R^2 = 0.876$), demonstrating that moisture moderates the density-conductivity relationship. Notably, the interaction term suggests a nonlinear dependence on both factors.
To better illustrate the combined influence of density and moisture content of wood on thermal conductivity, a 3D regression surface plot ‘Figure 5’ was generated using best-performing model. The surface plot visually confirms that:
- Higher wood moisture content levels amplify thermal conductivity increase, particularly in denser specimens;
- At lower moisture contents, density is dominant factor, while at higher moisture levels, both variables interact significantly.

These findings suggests that future revisions to ISO thermal conductivity models should incorporate moisture-density interactions for wood-based products to improve predictive accuracy, including CLT construction products.

Figure 5

Combined influence of Density and MC of Wood on CLT Thermal Conductivity



Consistent with the fundamental solid-wood studies of MacLean (1941), Kollmann & Côté (1968) and Tenwolde et al. (1988), we observed that thermal conductivity rises with both density and wood moisture content; however, our CLT-specific data reveal λ-values at 20 °C equilibrium temperature that are roughly 10 to 15 % lower than those prescribed by ISO 10456, a divergence that mirrors the field findings of Flexeder et al. (2021) and signals that the standard reference data tables may need updating for modern mass-timber products.

Conclusions

1. Experimental results confirm that CLT thermal conductivity is strongly correlated with density and wood moisture content, while thermal equilibrium effects on the measurements were found to be insignificant.
2. An increase in moisture content leads to a rise of CLT thermal conductivity, with this effect being more pronounced in higher density samples.
3. When comparing experimental data with ISO 10456 standard values, systematic discrepancies were observed – the standard models overestimate thermal conductivity across different density categories, potentially leading to inaccuracies in building energy efficiency calculations.
4. The obtained data suggest that interaction between moisture and density in CLT is a significant factor that should be considered when designing buildings, particularly in external envelope applications.
5. The study's findings provide a contribution to refining the thermal properties of CLT and offer improvements for updating standards and regulations related to the energy efficiency of mass timber structures.
6. The results contribute to a better understanding of how moisture and density influence CLT thermal conductivity and offer practical guidance for further investigation of laminated wood-based products.

Acknowledgements

In accordance with the contract No. 5.1.1.2.i.0/1/22/A/CFLA/007 between 'Forest Sectore Competence Centre of Latvia' Ltd. and the Central Finance and Contracting Agency, the study is conducted by 'Meža un koksnes produktu pētniecības un attīstības institūts' Ltd. With support from the European Regional Development Fund (ERDF) within the framework of the 'Forest Sectore Competency Centre' project P13 – 'Investigation of Timber Construction Utilization Possibilities for Specific Agricultural Production Buildings'.

References

Avramidis, S. & Liadis, L. (2005). Predicting wood thermal conductivity using artificial neural networks. *Wood and Fiber Science*, *37*(4), 682–690. https://wfs.swst.org/index.php/wfs/article/view/260/260

European Committee for Standardization. (2002a). *EN 13183-1, Moisture content of a piece of sawn timber - Part 1: Determination by oven dry method*. https://standards.cencenelec.eu/dyn/www/f?p=CEN:110:0::::FSP_PROJECT,FSP_ORG_ID:7840,6156&cs=1E3B3D0DB00D168F28956F46B7149A0EB

European Committee for Standardization. (2002b). *EN 13183-2, Moisture content of a piece of sawn timber - Part 2: Estimation by electrical resistance method*. https://standards.cencenelec.eu/dyn/www/f?p=CEN:110:0::::FSP_PROJECT,FSP_ORG_ID:7839,6156&cs=1AB1707CA3395EDE8AA00C853E27C63B5

European Committee for Standardization. (2005). *EN 1995-1-1, Eurocode 5: Design of timber structures - Part 1-1: General - Common rules and rules for buildings*. https://standards.cencenelec.eu/dyn/www/f?p=CEN:110:0::::FSP_PROJECT,FSP_ORG_ID:12423,6231&cs=1EF2FFF3D85978F4265162310ECD2E4CD

European Committee for Standardization. (2016a). *EN 338, Structural timber - Strength classes*. https://standards.iteh.ai/catalog/standards/cen/492c108d-268a-4cbd-9b59-3f31792887c5/en-338-2016?srsltid=AfmBOooW0Xxa1rvsAr6wsEpo-wN1wdb52kCkMomNVikW0Jxwwn3Z7kEC

European Committee for Standardization. (2016b). *EN 14358, Timber structures - Calculation and verification of characteristic values*. https://standards.cencenelec.eu/dyn/www/f?p=CEN:110:0::::FSP_PROJECT,FSP_ORG_ID:38069,6106&cs=16E06C974718474C9AFFF84B24AAF3B86

European Committee for Standardization. (2020). *EN 14081-1+A1, Timber structures - Strength graded structural timber with rectangular cross section - Part 1: General requirements*. https://standards.cencenelec.eu/dyn/www/f?p=CEN:110:0::::FSP_PROJECT,FSP_ORG_ID:69754,6106&cs=19190E2F9DE1B22A74E11E6D782625442

European Organisation for Technical Assessment. (2015). *EAD 130005-00-0304, Solid wood slab element to be used as a structural element in buildings*. https://www.eota.eu/download?file=/2013/13-13-0005/ead%20for%20ojeu/ead-130005-00-0304-solid-wood-slab-element-structural-element-in-buildings_ojeu.pdf

European Committee for Standardization. (2001). *EN 12667, Thermal performance of building materials and products - Determination of thermal resistance by means of guarded hot plate and heat flow meter methods - Products of high and medium thermal resistance*. https://standards.cencenelec.eu/dyn/www/f?p=CEN:110:0::::FSP_PROJECT,FSP_ORG_ID:2314,6072&cs=1C00E294960FB7969D7A8BBE335C6C397

Flexeder, N., Ott, S., Bodemer, E. & Winter, S. (2021). Monitoring of an office building in uninsulated cross laminated timber construction regarding hygrother-mal component behavior behavior. *Proceedings of the 2021 World Conference on Timber Engineering*. https://doi.org/10.14459/2022md1636556

Hunt, J. F., Gu, H. & Lebow, P. K. (2008). Theoretical thermal conductivity equation for uniform density wood cells. *Wood and Fiber Science*, *40*(2), 167–180. https://www.researchgate.net/publication/43269587_Theoretical_thermal_conductivity_equation_for_uniform_density_wood_cells

International Organization for Standardization. (2007). *Building materials and products - Hygrothermal properties - Tabulated design values and procedures for determining declared and design thermal values (ISO 10456)*. https://www.iso.org/standard/40966.html

International Organization for Standardization. (2017). *Thermal performance of windows, doors and shutters — Calculation of thermal transmittance Part 2: Numerical method for frames (ISO 10077-2)*. https://www.iso.org/standard/64995.html

Kollmann, F. & Côté, W. A. (1968). *Principles of wood science and technology. I. Solid wood*. Springer-Verlag.

MacLean, J. D. (1941). Thermal Conductivity of Wood. *Heating, Piping & Air Conditioning*, *13*(6), 380–391.

NETZSCH-Gerätebau GmbH. (n.d.). *HFM 436 Lambda: High Precision Instrument for Testing Insulating Materials*. Retrieved 17 March 2025, from https://www.netzsch.com

Tenwolde, A., Mcnatt, J. D. & Krahn, L. (1988). *Thermal Properties of Wood and Wood Panel Products for Use in Buildings*. Part of the National Program for Building Thermal Envelope Systems and Materials. Prepared for the U.S. Department of Energy Conservation and Renewable Energy Office of Buildings and Community Systems Building Systems Division. https://www.fpl.fs.usda.gov/documnts/pdf1988/tenwo88a.pdf

Wilkes, K. E. (1988). *Thermophysical properties data base activities at Owens-Corning Fiberglas*. ASHRAE Winter Meeting, Granville, Ohio, 662–667. https://web.ornl.gov/sci/buildings/conf-archive/1979%20B1%20papers/048.pdf