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EXPERIMENTAL EVALUATION OF HYGROTHERMAL PROPERTIES OF CHILEAN RADIATA PINE CROSS-LAMINATED TIMBER PANELS FOR CONSTRUCTION APPLICATIONS.

Paula Salgado[1], Cecilia Bustos[2], Gerardo Saelzer[3]

ABSTRACT: Cross-Laminated Timber (CLT) presents significant challenges due to its sensitivity to moisture, particularly under temperate-humid climates. As a hygroscopic material, wood exchanges moisture with the environment, causing dimensional changes that affect the stability and energy efficiency of CLT constructions. This study evaluates the hygrothermal properties of CLT manufactured using Chilean radiata pine, a material known for its mechanical performance and local availability. Employing rigorous laboratory testing compliant with Chilean (NCh 850, NCh 851) and European UNE-EN 323/322 standards, thermal conductivity, density, moisture content, and water vapor resistance were measured for CLT samples classified as C16 and C24. While Chilean standards were employed for experimental testing, comparisons with international standards are proposed to expand the global applicability of the results.

Results reveal that while adhesives slightly influence thermal properties, the overall hygrothermal performance remains robust, showcasing the material's suitability for sustainable construction in challenging climatic conditions. The findings have significant scientific and technological relevance, as they establish a baseline for optimizing CLT design and treatment strategies to mitigate moisture-related risks. Practically, the study provides actionable insights for architects and engineers aiming to enhance energy efficiency, structural stability, and durability in buildings using CLT in temperate-humid environments.

KEYWORDS: Cross-laminated timber (CLT), Hygrothermal properties, radiata pine, Massive timber

1 – INTRODUCTION

Cross-Laminated Timber (CLT) stands out for its structural strength, sustainability, and durability, making it a viable alternative for construction in Chile. The abundance and rapid growth of radiata pine, along with its good mechanical properties, position it as a suitable option for CLT manufacturing in the country. However, to optimize its use, it is essential to understand its hygrothermal characteristics.

CLT is composed of layers of wood arranged at right angles and bonded with structural adhesives [1]. Introduced in Austria and Germany in the 1990s, this material allows for the utilization of lower-quality wood [2]. Designed for high-rise constructions, CLT offers benefits such as sustainability and the reduction of carbon footprint due to CO_2 storage. Additionally, it provides dimensional and structural stability, thermal and acoustic insulation, lateral stiffness, good seismic performance, and thermal inertia.

Despite its advantages, CLT faces challenges such as the perception of wood as less resistant than reinforced concrete or steel and its sensitivity to moisture changes. Wood is a hygroscopic material that absorbs and releases water in response to variations in ambient humidity, which can lead to dimensional changes, swelling, or shrinkage, affecting the structural stability and energy efficiency of CLT constructions [3-4].

In addition, CLT is gaining popularity as an alternative to conventional construction materials due to its environmental benefits. These include carbon sequestration and reduced carbon footprints during its life cycle [5]. Prefabrication further enhances its appeal

[1] Paula Salgado, Ph.D student, University of Bio Bio, Chile; Departamento de Obras Civiles, Facultad de Ciencias de la Ingeniería, Universidad Católica del Maule, Av. San Miguel 3605, Talca 3460000, Chile, psalgador@ucm.cl

[2] Cecilia Bustos, full professor, University of Bio Bio, Chile; CENAMAD, cbustos@ubiobio.cl

[3] Gerardo Saelzer, associated Professor, University of Bio Bio, Chile, gsaelzer@ubiobio.cl

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by enabling faster construction times and reducing on-site waste [6].

1.1 DEFINITION AND APPLICATIONS OF CLT

CLT is a construction material composed of cross-laminated timber layers bonded with structural adhesives. This configuration provides high strength and stiffness, allowing its use in structural applications such as walls, floors, and roofs in mid-rise and high-rise buildings [7]. Beyond its structural benefits, CLT offers enhanced thermal and acoustic insulation, providing better energy efficiency compared to traditional materials.

1.2 HYDROTHERMAL PROPERTIES OF CLT

The hygrothermal performance of CLT, encompassing moisture absorption, thermal conductivity, and water vapor permeability, is critical to its behavior in diverse climatic conditions. As a hygroscopic material, wood absorbs and releases moisture, responding dynamically to ambient humidity [8].

Moisture Absorption and Dimensional Stability: Excess moisture can cause swelling and deformation. Studies show that the Equilibrium Moisture Content (EMC) of CLT is influenced by species and environmental conditions, with radiata pine exhibiting higher EMC values, making it more susceptible in humid environments [9].

Thermal Conductivity: Wood’s thermal conductivity increases with moisture content, which reduces energy efficiency in buildings [8].

Water Vapor Permeability: Proper vapor permeability helps manage moisture accumulation, reducing condensation risks. Using vapor barriers and breathable membranes is crucial for optimal performance [10].

1.3 CHALLENGES IN TEMPERATE-HUMID CLIMATES

This study directly addresses these challenges by experimentally evaluating the hygrothermal properties of radiata pine CLT. Specifically, it seeks to quantify how moisture conditions affect dimensional stability and water vapor resistance. This approach not only advances the scientific understanding of the material but also has practical implications for designing building envelopes that mitigate risks such as structural deformation and thermal efficiency loss in temperate-humid climates.

In temperate-humid climates, such as central and southern Chile, CLT faces additional challenges, including:

Mold and Fungal Growth: High humidity promotes biological degradation, compromising aesthetics and structural integrity [11].

Dimensional Deformation: Variations in moisture content cause swelling and shrinkage, affecting structural performance [12].

Mechanical Property Loss: Excessive moisture absorption diminishes the material's load-bearing capacity [13].

1.4 STRATEGIES TO ADDRESS HYDROTHERMAL RISKS

To ensure the effective use of CLT in challenging climates, mitigation strategies include:

Protective Treatments: Chemical treatments can enhance resistance to biological decay and reduce hygroscopic behavior, although environmental impacts must be considered [14].

Envelope Design: Incorporating vapor barriers, waterproof membranes, and effective drainage systems can mitigate moisture ingress [10].

Maintenance and Monitoring: Regular maintenance and moisture monitoring systems can identify issues early, preventing significant structural problems [15].

1.5 RESEARCH OBJECTIVES

The primary objective of this study is to determine the physical properties of Cross-Laminated Timber (CLT) manufactured from Chilean radiata pine, focusing on its hygrothermal behavior under temperate-humid climatic conditions characteristic of central-southern Chile. The findings aim to inform design and treatment strategies that optimize the use of CLT in practical applications, promoting its adoption as a sustainable building material in complex climatic contexts. By characterizing these fundamental properties, the research aims to establish a robust baseline of data that can inform future studies and advancements in the design, manufacturing, and application of CLT in various climatic conditions.

This foundational knowledge is essential for understanding the material's behavior under different environmental exposures, particularly in temperate-humid climates, and for optimizing its performance in sustainable construction practices. Furthermore, the results of this study will contribute to the development of standardized methodologies for evaluating the hygrothermal and physical performance of CLT, thereby supporting the broader adoption of radiata pine CLT as a viable material in the global construction market.

2 – MATERIALS AND METHODS

The materials used in this study are radiata pine timber sourced from forests in southern Chile (Mulchén, Bucalemu, and Nacimiento). Two structural grades, C16 and C24, classified according to their modulus of elasticity, were selected for panel fabrication. A polyurethane-based adhesive, Purbond HB S 109, was used for bonding the layers.

2.1 PANEL FABRICATION PROCESS

Adhesive Application: The polyurethane-based adhesive (Purbond HB S 109) was uniformly applied to ensure consistent bonding between the three laminae. Adhesive curing times were controlled for accuracy, using a hydraulic press at a pressure of 8 bar for 30 minutes, with opening times under temperatures between 5°C and 12°C and relative humidity between 50-70%. Typically, the thickness of CLT used in wall construction ranges from 75 mm to 150 mm; however, for thermal conductivity testing, 50 mm thick CLT was fabricated due to laboratory equipment limitations.

The CLT panels produced consist of three layers, laminated with two 30 mm solid timber layers and a 30 mm plywood core (lamina-plywood-lamina).

2.2 LABORATORY TEST

The experimental process involved fabricating CLT panels with three layers of 30 mm-thick laminae. The following tests were conducted:

Density and Moisture Content: Determined using UNE-EN 323 [16] and UNE-EN 322 standards. Additional measurements were performed using NCh 176/1.
Thermal Conductivity: Evaluated using the guarded hot plate method following NCh 850.
Thermal Transmittance: Measured in a thermal chamber according to NCh 851.
Water Vapor Transmission: Analyzed under the dry-cup method in compliance with NCh 2457:2014.

2.2.1 Apparent Density

The apparent density of the CLT specimens was determined following the procedures outlined in the UNE-EN 322 standard. This standard specifies the method for measuring the density of wood-based panels, including laminated timber such as CLT.

The density equation provides a fundamental measure of the material's mass per unit volume, which directly influences its structural performance and thermal behavior. Higher density often correlates with increased mechanical strength and slightly higher thermal conductivity, as observed in the C24 grade panels in this study. This relationship is critical when specifying materials for load-bearing applications in humid climates, where dimensional stability is also a factor.

To perform the test:

Specimens: The specimens used for the test consisted of CLT blocks of structural quality C16 and C24 with dimensions of 90 mm × 90 mm × 90 mm thickness.

Weighing the Specimens: Each specimen was weighed to determine its mass (mmm) using a precision digital scale with an accuracy of at least 0.01 g.

Volume Measurement: The dimensions of each specimen (L, W, and T) were carefully measured using a digital caliper with an accuracy of 0.1 mm to calculate the volume (V) of the specimens.

Density Calculation: The apparent density (ρ)was calculated using the following equation:

$$\rho = m/v \qquad (1)$$

Where:
ρ = Apparent density of the sample, Kg/m³.
m = Mass of the specimen in anhydrous conditions, Kg.
V = Volume of the specimen with a moisture content of 12%, m³, calculated as $V=L\times W\times T$

For this type of case, where this type of density is calculated for this material, a moisture content of 12% must be used.

The measurements were conducted under controlled environmental conditions to minimize errors due to moisture variations. Specifically, the specimens were conditioned at a temperature of 20°C ± 2°C and relative humidity of 65% ± 5% until achieving a stable weight, ensuring that they reached equilibrium moisture content (EMC).

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The results were recorded and analyzed to determine the average apparent density for both structural grades (C16 and C24), providing a baseline for evaluating the physical performance of CLT panels in further tests.

2.2.2 Thermal Conductivity

In accordance with technical specifications, the specimens consisted of C16 and C24 CLT blocks with dimensions of 300 mm × 300 mm × 50 mm thickness.

The apparatus used consists of a central metal plate (hot plate) equipped with electric heating. This plate is surrounded by a guard ring, which can be independently heated. On either side of the plates, two specimens with equal dimensions and flat parallel surfaces were placed. Cold metal plates with water circulation (cold plates) were positioned in contact with the specimens, forming a sandwich-like assembly. See Figure 2.

The method involves measuring the heat flux electrically produced in the hot plate under steady-state conditions, which passes through both specimens while recording their respective surface temperatures. The measurement area, equal to the hot plate area, is 0.0255 m²; the specimens measured 0.3 × 0.3 m with a maximum thickness of 50 mm. According to the design of the apparatus, the specimens were oriented vertically during testing.

The thermal conductivity of the material was calculated the following equation:

$$\lambda = \frac{\emptyset * e}{2A\,(T_2 - T_1)} \qquad (2)$$

λ: Thermal conductivity, (W/m·K).

$\emptyset$: Heat flux through the material, (W).

e: Average thickness of both specimens (m).

A: Measurement area, (m2).

$T_2 - T_1$: Average temperatures of hot and cold surfaces, (K).

Figure 1 illustrates the guarded hot plate apparatus used to measure thermal conductivity under steady-state conditions. The sandwich-like assembly ensures uniform heat transfer, with the hot plate simulating internal building temperatures and the cold plates mimicking external climatic conditions. This setup replicates real-world scenarios, enabling accurate assessment of insulation performance in building applications.

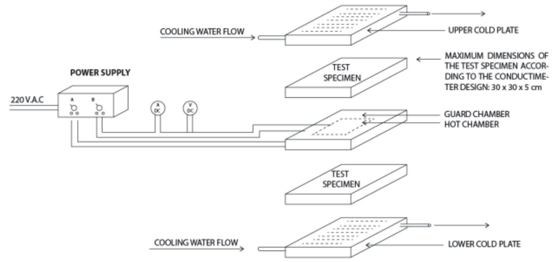

Figure 1: Experimental Setup – Thermal Conductivity

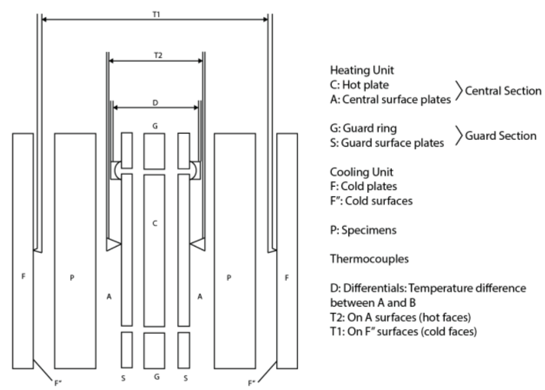

Figure 2: Diagram of the Hot Plate Apparatus with Guard Ring.

The thermal conductivity equation (λ = Φ * d / (A * ΔT)) quantifies the material's ability to conduct heat. In this context, Φ represents the heat flux, d the average panel thickness, A the measurement area, and ΔT the temperature gradient. This parameter is crucial for designing energy-efficient building envelopes, as lower λ values indicate better insulation performance. The slight increase in λ due to adhesive layers was found to be negligible, supporting the material's suitability for energy-efficient construction.

2.2.3 Water Vapor Resistance Factor

In accordance with technical specifications, the specimens were C16 and C24 CLT blocks measuring 160 mm × 160 mm × 90 mm thickness.

The methodology used for determining water vapor permeability properties followed the NCh 2457:2014 standard.

This is achieved by controlling the environmental variables during testing and promoting vapor pressure differentials through a desiccant or liquid medium. Two test methods are defined: wet-cup and dry-cup. The dry-cup method was used in this evaluation to determine vapor diffusion properties, which occur under low-humidity conditions, typical for technical material specifications.

The method involves placing the test specimen (160 mm × 160 mm) on a vapor-resistant plate. The desiccant behavior is verified, and the plate is sealed using 60% microcrystalline wax and 40% refined paraffin wax to prevent errors due to vapor leakage.

Figure 3 depicts the dry-cup method used to evaluate water vapor permeability under controlled low-humidity conditions. The setup simulates real-life scenarios where materials are exposed to vapor gradients, allowing for precise measurement of diffusion properties. This test is crucial for optimizing moisture management in construction, particularly in climates prone to condensation issues. See Figure 3.

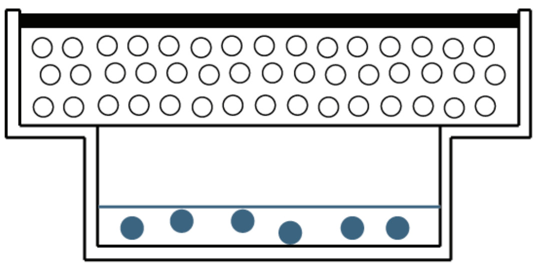

Figure 3: Dry-Cup Method Setup for Water Vapor Permeability.

The specimens were placed in a drying oven under controlled temperature and humidity conditions. Measurements were taken daily at a specific time until the specimen achieved hygrothermal stability with respect to its weight.

Finally, the water vapor resistance factor was calculated as the ratio of air vapor permeability to the material's water vapor permeability using the following equation:

$$\mu = \frac{\delta a}{\delta m} \quad (3)$$

Where:

μ: Water vapor resistance factor (adimensional)

δa: Water vapor permeability of air (kg/(m·s·Pa))

δm: Water vapor permeability of the material (kg/(m·s·Pa))

The water vapor resistance factor (μ = δa / δm) highlights the material's capability to resist vapor diffusion compared to air. High μ values, as observed in radiata pine CLT, ensure that vapor barriers and membranes can be optimized to mitigate condensation risks. This property is particularly significant in temperate-humid climates, where excessive vapor diffusion can compromise structural integrity.

2.2.4 Thermal Transmittance (U-Value)

The calibrated thermal chamber used consists of three chambers, which are boxes open on one side:

1. Guard or hot chamber (1.85 × 1.85 m)
2. Cold chamber
3. Measuring or protected chamber (1.0 × 1.0 m)

See figure N°4.

The method is based on determining, under steady-state conditions, the heat flux passing through a building element and the corresponding temperatures over a measurement area of 1.0 m².

The CLT specimen 1390 mm × 1550 mm × 90 mm thickness was positioned vertically between the thermal chambers. The hot chamber simulated a warm environment using adjustable electrical resistances, while the cold chamber simulated a cold environment using a conventional refrigeration unit. Under these conditions, heat flowed through the specimen, with the amount of heat inversely proportional to its thermal insulation.

The thermal transmittance (U-value) was determined using the following equation:

$$U = \frac{\Phi}{A * \Delta Taa}$$

Where:

U: Thermal transmittance (W/m²·K)

Φ: Heat flux through the specimen (W)

ΔTaa: Average temperature difference: air-air on both sides of the element (K)

A: Measurement area (m²)

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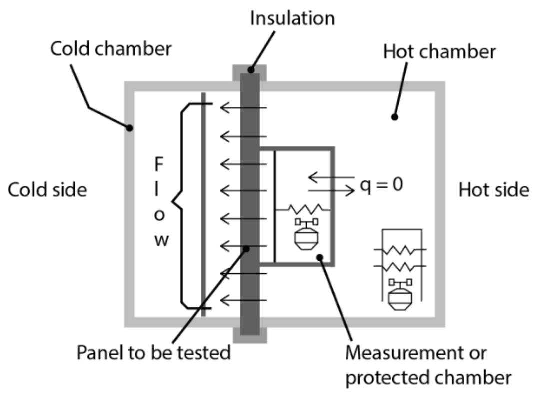

Figure 4: Experimental Setup for Thermal Transmittance Testing.

3 – RESULTS AND DISCUSSION

3.1 THERMAL PROPERTIES OF CLT PANELS

3.1.1 Thermal Conductivity

The thermal conductivity values measured in this study as seen in figure 5, indicate that CLT panels maintain good thermal performance, even with slight increases in conductivity due to adhesive integration. This finding has significant implications for energy-efficient building design in temperate-humid climates, where managing heat transfer is critical to reducing energy consumption for heating and cooling. By using CLT panels, architects and engineers can achieve better insulation compared to conventional materials, contributing to both operational energy savings and occupant comfort.

Thermal conductivity values for CLT panels were measured as follows:

- C16: 0.123 W/mK

- C24: 0.132 W/mK

Panel Dimensions: Samples measured 300x300x50 mm, with each lamina 30 mm thick. Testing Conditions: All laboratory experiments adhered to controlled temperature (20°C) and humidity conditions (65% relative humidity).

These values are higher than solid radiata pine (0.104 W/mK), which can be attributed to the influence of the adhesive. However, the overall increase is minimal, ensuring that the panels maintain good thermal performance.

3.1.2 Thermal Transmittance

The thermal transmittance values measured were:

- C16: 1.28 W/m²K

- C24: 1.24 W/m²K

The results indicate that CLT panels meet insulation requirements for temperate-humid climates. The slight differences between C16 and C24 are due to variations in density and adhesive integration.

3.2 HYGROTHERMAL PERFORMANCE IN HUMID CONDITIONS

The results obtained demonstrate that CLT panels maintain good dimensional stability under high humidity conditions. This behavior is crucial for ensuring the durability and thermal performance of buildings in temperate-humid climates, where moisture accumulation can compromise both structural integrity and energy efficiency.

Water vapor transmission tests showed consistent performance under dry-cup conditions. The mass variations observed over 14 days were minimal, confirming that the CLT panels exhibit good resistance to water vapor and dimensional stability.

3.3 PHYSICAL PROPERTIES OF RADIATA PINE

3.3.1 Density and Moisture Content

The uniform density and moisture content observed in radiata pine CLT panels demonstrate the material's consistency and suitability for industrial processes. This consistency facilitates standardization in manufacturing, enabling efficient production and quality control. Additionally, the reliable performance of CLT panels enhances their competitiveness in the global market, positioning radiata pine CLT as an exportable product for sustainable construction.

The density and moisture content of the panels were as follows:

- C16: 450 kg/m³, 9.60% moisture content

- C24: 455 kg/m³, 9.85% moisture content

These values are within acceptable ranges, highlighting the homogeneity and quality of the material.

Table 1 summarizes the key thermal and physical properties of the tested CLT panels, highlighting their suitability for sustainable construction.

Figure 5: Laboratory test – Thermal Conductivity

Table 1: Summary of Thermal and Physical Properties of CLT Panels

Property	***C16 Value***	***C24 Value***	***Observations***
Thermal Conductivity (λ)	0.123 W/m·K	0.132 W/m·K	Adhesive increases conductivity slightly compared to solid radiata pine (0.104).
Thermal Transmittance (U)	1.28 W/m²·K	1.24 W/m²·K	Slightly better insulation in C24 panels due to higher density.
Density (ρ)	450 kg/m³	455 kg/m³	Minor difference; material consistency validated.
Moisture Content (%)	9.60%	9.85%	Within acceptable construction ranges, ensuring stable behavior.

3.3.2 Hygrothermal Performance

Stability under varying humidity conditions was analyzed using the dry-cup method, focusing on weight changes over 14 days. Table 2 presents the results of mass variation during water vapor transmission tests, demonstrating the material's hygrothermal stability under controlled conditions.

Table 2: Results of Mass Change During Water Vapor Transmission Tests

Sample	***Initial Weight (g)***	***Final Weight (g)***	***Weight Change (g)***	***Observation***
C16-1	1951.82	2005.95	+54.13	Stable
C16-2	1921.05	2005.88	+84.83	Stable
C16-3	2145.00	2006.10	-138.90	Stable
C24-1	2047.52	2111.39	+63.87	Stable
C24-2	2033.74	2111.34	+77.60	Stable
C24-3	2252.92	2111.55	-141.37	Stable

3.4 CONTRIBUTION TO LITERATURE AND PRACTICE

The findings of this study provide actionable insights for informing design strategies and construction policies in Chile and regions with temperate-humid climates.

The results presented in Table 1 highlight the competitive thermal conductivity (0.123–0.132 W/m·K) and transmittance (1.24–1.28 W/m²·K) values of radiata pine CLT compared to conventional construction materials such as concrete and steel. These properties make CLT an ideal material for energy-efficient building designs in temperate-humid climates, aligning with global sustainability goals.

Furthermore, the consistent density (450–455 kg/m³) and moisture content (9.6–9.85%) validate the material's homogeneity and reliability for industrial applications. This consistency ensures standardized performance, facilitating its adoption in both local and international markets.

Table 2 demonstrates the excellent hygrothermal stability of CLT panels under controlled humidity conditions. The minimal weight variations observed during the 14-day water vapor transmission tests indicate strong resistance to moisture-related deformation. These results provide crucial insights for optimizing moisture management strategies, such as the integration of vapor barriers and drainage systems in CLT-based construction.

The stable performance observed across both C16 and C24 grades suggests that architects and engineers can confidently specify either grade based on project-specific requirements, ensuring durability and structural integrity in buildings exposed to high humidity environments.

The data from Tables 1 and 2 support key recommendations for integrating radiata pine CLT into sustainable construction practices. Specifically, the combination of superior thermal performance and moisture resistance enables the design of building envelopes that reduce energy consumption while ensuring long-term durability. These findings are particularly relevant for regions like Chile, where temperate-humid climates pose unique challenges to construction materials.

The uniformity in density and moisture content, as shown in Table 1, reinforces the potential for mass production and exportation of radiata pine CLT to markets with similar climatic conditions. Meanwhile, the hygrothermal stability outlined in Table 2 underscores the necessity of adopting CLT in policies promoting low-carbon and energy-efficient construction materials.

In Chile, where the construction sector increasingly prioritizes sustainability, these findings support the adoption of CLT as a low-carbon alternative to traditional materials such as concrete and steel. By ensuring that CLT panels maintain structural and thermal integrity even in challenging climates, this research provides a foundation for expanding CLT applications in

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residential, commercial, and institutional buildings across regions with similar climatic conditions worldwide.

The findings of this study provide actionable insights for informing design strategies and construction policies in Chile and regions with temperate-humid climates:

The low thermal conductivity and high moisture resistance of radiata pine CLT make it an ideal material for designing energy-efficient and durable building envelopes, particularly in coastal and southern regions of Chile where high humidity is prevalent.

These results highlight the importance of integrating vapor barriers and drainage systems in timber-based constructions to ensure long-term performance.

Results can be use to promote radiata pine CLT as a sustainable, low-carbon material aligned with Chile's national green building initiatives and carbon neutrality goals.

Given its suitability for temperate-humid climates, radiata pine CLT can be positioned as an exportable product to markets with similar climatic conditions, such as New Zealand, Australia, and parts of Europe, with appropriate harmonization to international standards.

3.5 COMPARISON WITH INTERNATIONAL STANDARDS

While the experimental methodology followed Chilean standards (NCh 850, NCh 851, NCh 2457), which are highly suitable for local contexts, comparisons with internationally recognized standards such as European Norms (EN) and ASTM could further enhance the applicability of the results. For example:

Thermal Conductivity (NCh 850 vs. EN 12667): The methodology outlined in NCh 850 aligns closely with EN 12667, both utilizing the guarded hot plate method. However, EN 12667 provides additional specifications for sample preparation (e.g., lateral insulation) and boundary conditions, which could improve the accuracy of measurements, particularly for thinner panels.

Water Vapor Resistance (NCh 2457 vs. EN ISO 12572): While both standards employ the dry-cup and wet-cup methods, EN ISO 12572 includes broader climate chamber controls, enabling testing under variable humidity gradients. This flexibility could offer insights into performance under extreme climatic conditions.

Apparent Density (UNE-EN 323 vs. ASTM D2395): Both standards evaluate density under controlled conditions, but ASTM D2395 provides alternative methods for measuring density variations within larger specimens, potentially enhancing accuracy for industrial applications.

The thermal conductivity and transmittance values obtained for radiata pine CLT panels (C16: 0.123 W/mK, C24: 0.132 W/mK) align closely with similar studies on softwoods used in construction, such as European spruce and Douglas fir. These materials typically demonstrate thermal conductivity values in the range of 0.11–0.14 W/mK, confirming that radiata pine is competitive for insulation in sustainable building designs.

When compared to traditional materials like concrete (1.7 W/mK) and steel (50 W/mK), CLT demonstrates a significantly lower thermal conductivity, making it a superior choice for reducing thermal bridging in building envelopes. This characteristic directly contributes to lower energy consumption in heating and cooling, aligning with global sustainability goals in architecture.

Additionally, the hygrothermal stability observed under temperate-humid conditions provides a compelling case for the adoption of radiata pine CLT in climates similar to Chile, such as New Zealand, Australia, and parts of Europe. These findings position CLT as a sustainable alternative for energy-efficient and low-carbon construction.

4 – CONCLUSIONS

The findings of this study provide a robust foundation for the implementation of radiata pine CLT in temperate-humid climates. The detailed characterization of its hygrothermal properties will enable designers and builders to make informed decisions regarding material selection, envelope design, and moisture protection strategies, fostering more efficient and sustainable construction practices. The key findings include:

Thermal conductivity and transmittance values are within acceptable ranges for energy-efficient construction. Adhesive integration slightly increases conductivity but does not compromise insulation performance.

Panels exhibit good resistance to water vapor, ensuring dimensional stability under humid conditions.

Future research should focus on optimizing adhesives and incorporating protective treatments to enhance performance further under varying climatic conditions.

The comprehensive analysis of CLT panels indicates their suitability for temperate-humid climates: Thermal insulation meets performance expectations, with minor adhesive impacts.

Stable water vapor resistance ensures long-term structural integrity.

Compared to traditional construction materials, radiata pine CLT demonstrates superior thermal insulation and moisture control, making it a sustainable choice for energy-efficient buildings. By aligning these findings with global benchmarks for sustainable design, this study provides actionable insights for architects, engineers, and policymakers aiming to reduce the environmental footprint of construction.

Consistency in density and moisture content confirms material quality.

The exclusive use of Chilean standards provided highly relevant data for the local context; however, future studies could incorporate EN and ASTM standards to ensure broader comparability and marketability. Such alignment would not only validate radiata pine CLT for use in international construction but also establish a robust framework for exporting this material to regions with similar climatic conditions.

The recommendations derived from this study emphasize the importance of integrating radiata pine CLT into energy-efficient and moisture-resistant building practices. By adopting these strategies, Chile and other regions with temperate-humid climates can promote sustainable construction while ensuring durability and performance. Future efforts should focus on policy adjustments, international standard alignment, and continued innovation in CLT technologies.

Future research should evaluate alternative adhesives and protective coatings to enhance hygrothermal performance under more severe environmental conditions.

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REFERENCES

[1] Mohammad, M., Gagnon, S., Douglas, B. K., & Podesto, L. (2012). Introduction to cross laminated timber. Wood Design Focus, 22(2), 3-12.

[2] Karacabeyli, E., & Douglas, B. (2013). CLT handbook. US Edition. FPInnovations and Binational Softwood Lumber Council, Point-Claire, Quebec.

[3] Pang, S. J., & Jeong, G. Y. (2020). Swelling and shrinkage behaviors of cross-laminated timber made of different species with various lamina thickness and combinations. Construction and Building Materials, 240, 117924.

[4] Gülzow, A., Richter, K., & Steiger, R. (2011). Influence of wood moisture content on bending and shear stiffness of cross laminated timber panels. European Journal of Wood and Wood Products, 69(2), 193-197.

[4] Brandner, R., Flatscher, G., Ringhofer, A., Schickhofer, G., & Thiel, A. (2016). Cross laminated timber (CLT): overview and development. European journal of wood and wood products, 74, 331-351.

[6] Mohammad, M., Gagnon, S., Douglas, B. K., & Podesto, L. (2012). Introduction to cross laminated timber. Wood Design Focus, 22(2), 3-12.

[7] Gagnon, S., & Pirvu, C. (2011). CLT handbook: cross-laminated timber.

[8] Glass, S., & Zelinka, S. (2021). Moisture relations and physical properties of wood. Chapter 4 in FPL-GTR-282, 4-1.

[9] Benedetti, F., Rosales, V., & Opazo, A. (2017). Cyclic behavior of foundation-wall connection in cross laminated timber shear walls. In 16th World Conference on Earthquake, 16WCEE.

[10] Cornick, S., Dalgliesh, A., Said, N., Djebbar, R., Tariku, F., & Kumaran, M. K. (2002). Report from Task 4 of MEWS Project-Task 4-Environmental Conditions Final Report. Institute for Research in Construction. Ottawa: National Research Council.

[11] Viitanen, H., Vinha, J., Salminen, K., Ojanen, T., Peuhkuri, R., Paajanen, L., & Lähdesmäki, K. (2010). Moisture and bio-deterioration risk of building materials and structures. Journal of building physics, 33(3), 201-224.

[12] Wang, G. (2018). Hygrothermal Performance of Southern Pine Cross-laminated Timber. North Carolina State University.

[13] Schmidt, E., & Riggio, M. (2019). Monitoring moisture performance of cross-laminated timber building elements during construction. Buildings, 9(6), 144.

https://doi.org/10.52202/080513-0689

[14] Jones, D., Sandberg, D., Goli, G., & Todaro, L. (2019). Wood Modification in Europe: a state-of-the-art about processes, products and applications (p. 123). Firenze University Press.

[15] Wang, L., & Ge, H. (2017). Effect of air leakage on the hygrothermal performance of highly insulated wood frame walls: Comparison of air leakage modelling methods. Building and environment, 123, 363-377.

[16] AENOR. (1993). UNE-EN 323: Wood-based panels. Determination of density.