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HYGROTHERMAL PERFORMANCE AND WATER VAPOUR DIFFUSION RESISTIVITY OF AUSTRALIAN PLANTATION-GROWN TIMBER

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ABSTRACT: This research investigates the hygrothermal performance of Cross-Laminated Timber (CLT) and solid wood products manufactured from Australian plantation-grown timber. Over the past three decades, the use of plantation softwood and hardwood, and engineered wood products in Australian buildings has increased. However, wood products can also provide a food source for mould growth in inappropriately designed or constructed façade systems, highlighting the need for accurate risk assessments concerning moisture transport, structural degradation, and adhesive failure. Understanding water vapour diffusion resistivity is crucial for conducting hygrothermal simulations, which support the design of moisture-resilient timber-based façades. This research explores water vapour diffusion resistivity in timber, identifying gaps in Australian plantation timber research. It examines laboratory-based methods for quantifying water vapour diffusion resistivity and approaches to validate hygrothermal simulations in full-scale buildings. The study highlights multi-RH gravimetric cup testing as the most effective method for improving hygrothermal modeling accuracy and moisture risk assessments. By establishing high-quality water vapour diffusion resistivity data, this research supports building professionals and regulators in making informed decisions, leading to energy-efficient, healthy, and durable buildings and promotes renewable timber resources in modern construction. This research contributes to industry best practices and regulatory advancements in timber-based construction.

KEYWORDS: Water vapour diffusion resistivity, Mould Index, plantation timber, Pinus radiata, Eucalyptus nitens timber.

1 – INTRODUCTION

Global initiatives aimed at enhancing building sustainability emphasize the need for empirical investigations into the hygrothermal performance of insulated wood-framed structures, solid wood, and engineered-wood façade systems. Wood-based construction materials play a significant role in reducing the carbon footprint of buildings, improving energy efficiency, and promoting sustainabilit [9]. However, the moisture behavior of timber-based materials remains a critical concern, as excess moisture can lead to mould growth, structural degradation, and compromised indoor air quality [82,1]. This research is part of a broader effort to explore the water vapour diffusion resistivity properties of solid wood and engineered wood products (EWPs), particularly those derived from Australian plantation timber. Accurate hygrothermal data is crucial for both design-based decision-making and forensic investigations of heat and moisture performance in building envelope systems that incorporate timber products. Since the 1930s, conferences have extensively explored the interrelationship between building material choices, interior climate control (heating, cooling, and ventilation), and condensation risks [70,10]. By the 1950s, standardized calculation methods were developed to predict condensation formation in

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building envelopes [14]. In the 1980s the introduction of building envelope airtightness was observed as a key strategy for improving energy efficiency [26,43]. However, increased airtightness was soon linked to higher moisture accumulation and mould risks, necessitating the integration of ventilation strategies to mitigate these effects [18]. During the 1990s, research highlighted the interaction between temperature, relative humidity, and mould growth on solid wood materials, leading to the development of mould growth prediction models [82]. These advancements, coupled with growing computing power, facilitated the emergence of transient hygrothermal simulation tools in the late 1990s and linked mould growth algorithms in 2007 [83]. The significance of these developments was reinforced by the World Health Organization (WHO) in 2009, which recommended that no visible or interstitial mould should be present within buildings due to its adverse effects on human health [29, 53,55]. Bomberg et al. (2017) further emphasized the importance of integrating energy efficiency, indoor air quality, and material durability into building design [5]. Subsequent studies have examined the hygrothermal performance of timber-based external wall systems in various Australian climates, highlighting the need for moisture safety and durability considerations in building design [7,16,20,21,45,60]. The practical implications of this research are substantial, providing architects, engineers, and policymakers with crucial material data [18,17]. Moreover, this study aligns with global sustainability goals, advocating for the increased use of renewable timber resources and enhancing the overall energy efficiency and durability of modern buildings [9].

2 - BACKGROUND

The hygrothermal performance of construction materials has been a significant focus of research for over a century, particularly in relation to moisture accumulation, condensation risks, and material degradation [39,40,70, 74]. Research on water vapour diffusion resistivity — a critical factor in evaluating a material's ability to limit or allow moisture movement—has evolved significantly alongside advancements in building science and energy efficiency standards[33,41]. Since the 1930s, studies have explored how building envelope materials, heating, cooling, and ventilation systems influence condensation and mould risks [39,40,83]. In the 1950s, established methods were introduced to estimate dew-point temperatures and predict condensation risks in wall assemblies [14]. By the 1980s, research emphasized the importance of airtightness in energy-efficient buildings, acknowledging that improved thermal insulation and reduced air leakage can lower energy consumption [19,26]. However, these airtight designs also led to higher moisture retention, increasing mould growth risks unless adequate ventilation strategies were implemented [6,18]. During the 1990s, research on hygrothermal modeling and transient moisture transport became more advanced, leading to the development of mould growth prediction models for solid wood and engineered wood products (EWPs) [82,83]. By the late 1990s, hygrothermal simulation tools such as WUFI Pro were developed to predict heat and moisture interactions within building assemblies, allowing for more precise moisture management strategies [33,41]. The World Health Organization (WHO) in 2009 reinforced the importance of hygrothermal analysis, recommending that no visible surface or interstitial mould should be present within buildings due to its adverse effects on occupant health [29,59]. This highlighted the need for accurate material property data—such as water vapour diffusion resistivity values—to improve hygrothermal simulations and mould risk assessments [8,91]. One of the most critical issues related to moisture exposure in timber structures is mould growth, particularly in solid wood elements. When solid wood absorbs excess moisture, it creates a favorable environment for mould spores to develop, leading to structural degradation and potential health risks [83,86]. Figure 1 below illustrates mould formation on a mix of solid-wood and engineered-wood elements within a well ventilated subfloor zone, emphasizing the importance of proper moisture control in timber-based construction.

Figure 1. Mould formation in wooden subfloor zone

In Australia, by 2014, researchers recognized the complex interaction between airtight building envelopes, weather-tightness, and ventilation strategies, emphasizing the importance of transient hygrothermal simulations in ensuring moisture safety and durability in timber-based construction [18,42, 58]. Further studies demonstrated that water vapour diffusion resistivity data for Australian-grown timber—particularly plantation-grown species like Radiata Pine and Eucalyptus Nitens—was largely absent from international hygrothermal databases, limiting the accuracy of moisture risk assessments for timber structures [7,25]. The shift from old-growth hardwood to plantation-grown softwood and hardwood in Australia has intensified the need for accurate hygrothermal data on these newer timber resources. Modern construction increasingly utilizes Cross-Laminated Timber (CLT) and other engineered wood products (EWPs), which have different moisture transport behaviours compared to traditional 'old-growth'solid wood materials. However, moisture exposure in EWPs presents additional challenges, including differential expansion between bonded layers, delamination risks, and weakening of adhesive bonds [23,37,86] As shown below (see Figure 2 delamination in CLT panels, a common issue caused by moisture penetration and inadequate bonding strength.

Figure 2 : Delamination In CLT [52].

Moisture accumulation can also cause mechanical property reductions, load-bearing capacity loss, and failure of connections such as nails and fasteners [8,76,79]. In CLT, moisture penetration between layers can lead to stress accumulation and micro-cracks, further accelerating structural deterioration Additionally, high moisture levels in timber construction can cause differential swelling, leading to warping, dimensional instability, and premature failure in load-bearing applications [11,86]. As shown in Figure 3, excessive moisture exposure results in visible cracks and damage in CLT, emphasizing the need for effective moisture management strategies [23,68].

Figure 3: Impact of Moisture on CLT [80].

Addressing these challenges requires comprehensive laboratory investigations into water vapour diffusion resistivity to improve hygrothermal modeling precision and optimize building design strategies [7].

This paper reviews the state of knowledge on water vapour diffusion resistivity, identifying critical gaps in Australian timber research and assessing the most appropriate laboratory methods to quantify these properties. The study also explores empirical validation techniques, such as full-scale test walls, to improve the accuracy of transient hygrothermal simulations. By generating high-quality input data for hygrothermal modeling, this research will contribute to the development of more energy-efficient, durable, and moisture-safe timber buildings.

3- WATER VAPOUR DIFFUSION IN TIMBER AND CLT

Engineered wood products (EWPs) are structurally optimized timber-based materials, manufactured by bonding multiple layers of wood veneers, strands, or boards with adhesives. Common EWPs include Cross-Laminated Timber (CLT), Glulam, Laminated Veneer Lumber (LVL), and Plywood, each offering improved strength, dimensional stability, and consistent performance compared to solid wood [66, 87]. These products have significantly advanced modern timber construction, enabling the development of high-rise wooden structures, prefabricated modular buildings, and sustainable building envelopes [9,24]. However, their moisture behavior and water vapour diffusion resistivity differ significantly from those of solid wood due to lamination processes, adhesive composition, and fiber orientation [22, 36]. Understanding how moisture moves through EWPs is critical for predicting hygrothermal performance, preventing mould and decay, and optimizing durability in varying climates [13,33, 90].

Water vapour diffusion resistivity (μ-value) is a key factor in evaluating the hygrothermal performance of timber-based construction systems, influencing durability, energy efficiency, and mould resistance. Unlike isotropic materials, timber exhibits anisotropic moisture diffusion, meaning diffusion rates vary based on grain orientation, species characteristics, and processing methods [12,84]. In solid wood, factors such as density, fiber saturation point (FSP), and anatomical structure influence diffusion behavior, with higher-density species (e.g., Eucalyptus Nitens) exhibiting lower permeability than lower-density species (e.g., Radiata Pine) [73,78]. However, limited empirical data exist for the water vapour diffusion resistivity of Australian-grown timber, leading to reliance on extrapolated values from European species, which may introduce inaccuracies in hygrothermal simulations [7,25]. In engineered wood products (EWPs), particularly Cross-Laminated Timber (CLT) and Glulam, adhesives play a key role in modifying moisture diffusion pathways. Adhesive layers within laminated wood act as barriers to water vapour diffusion, introducing moisture gradients that can result in differential swelling, shrinkage, and stress accumulation, potentially leading to adhesive failure in extreme conditions [28,75]. Studies indicate that increasing the ratio of glue lines to panel thickness in CLT enhances water vapour resistance, although the adhesive type itself has less direct impact on overall vapour resistance than factors such as bond thickness, distribution, and quality [36,50,61]. Imperfections, including voids or incomplete bonding, can accelerate moisture ingress, compromising the hygrothermal performance of the panel [67,68]. Additionally, different adhesives exhibit distinct hygrothermal properties; for example, polyurethane (PUR) adhesives, commonly used in CLT, provide strong mechanical bonding, but curing issues such as gas bubble formation can influence water vapour diffusion resistivity [72]. Epoxy adhesives, on the other hand, are known to lose tensile strength and elasticity when exposed to high moisture levels and temperatures, highlighting the necessity for moisture-resistant formulations in hygrothermal applications [49,88,91].

The impact of relative humidity variations on water vapour diffusion resistivity is particularly important, as μ-values are not static; they change depending on moisture exposure conditions [12,65]. At low RH (30%), timber exhibits higher resistivity, whereas at high RH (80%), increased moisture absorption causes cell walls to swell, reducing

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resistivity and allowing faster vapour diffusion [92]. This RH-dependent behavior influences WUFI hygrothermal simulations, where incorrect diffusion resistivity values can lead to miscalculations in moisture risk assessments [41]. Additionally, timber exhibits a hysteresis effect, meaning its diffusion characteristics differ during absorption versus desorption, further complicating moisture modeling [82,83]. Current international hygrothermal databases primarily contain diffusion resistivity values for European and North American softwoods, such as Spruce and Pine, widely used in cold-climate construction. These datasets inform building codes and moisture performance simulations. However, Australian-grown timber species, including Radiata Pine and Eucalyptus Nitens, lack empirical μ-values, necessitating experimental validation. Without accurate species-specific data, applying extrapolated values from European species may lead to errors in moisture control strategies for Australian buildings. This research aims to fill that gap by measuring water vapour diffusion resistivity under multiple RH conditions, using gravimetric cup methods [2,34], ensuring that Australian-grown plantation timber is accurately represented in hygrothermal simulations for moisture performance assessments.

4- REVIEW OF METHODOLOGIES FOR DETERMINING WATER VAPOUR DIFFUSION RESISTIVITY IN CONSTRUCTION MATERIALS

The accurate determination of water vapour diffusion resistivity is essential for understanding the moisture transport properties of solid wood and engineered wood products (EWPs) used in construction. Various laboratory-based and empirical validation methods exist, each differing in accuracy, applicability, and reliability. The Electronic-Analytical Method as illustrated in Figure 4 utilizes capacitive hygrometric sensors within a controlled cabinet to measure water vapour transmission rates. This method provides rapid, automated quality control for non-porous materials, making it useful for industrial applications such as coatings and films. However, it has limited applicability to porous materials like timber, as wood's hygroscopic nature makes sensor-based readings less reliable [71,89].sweating Guarded Hot Plate Method, as shown in Figure 5 is primarily applied in textile testing. This method evaluates heat and moisture transfer through a heated plate. It measures the resistance of materials to evaporative heat loss, making it useful for assessing clothing and insulation materials. However, it is unsuitable for bulk construction materials such as wood due to its inability to account for moisture movement through capillary action [31,85].

Figure 4 : Electronic method [81].

Figure 5: Assemblage of the equipment for sweat guarded hot plate [35]

The Dynamic Moisture Permeation Cell (DMPC) as shown in figure 6 method involves placing materials between controlled humidity chambers, ensuring precise moisture diffusion measurements in materials like polymer membranes. However, it is costly, requires specialized equipment, and lacks applicability to large-scale building materials like timber due to its inconsistent results in highly porous materials [27].

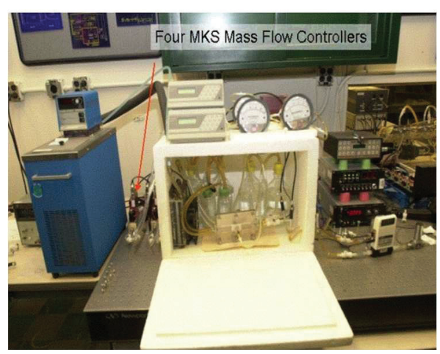

Figure 6: Equipment arrangement for DMPC testing

The isothermal sorption method examines moisture absorption and desorption under fixed temperatures while systematically adjusting humidity levels, providing detailed hygroscopic behavior insights. However, the requirement for extended equilibrium moisture content

(EMC) stabilization reduces its feasibility for rapid material assessments as shown 7 [2,3].

Figure 7: The isothermal sorption method

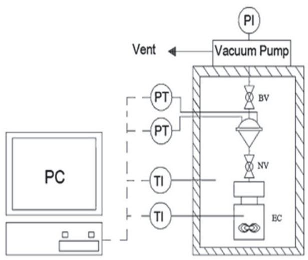

Figure 8: The vapour pressure method

The vapour pressure method As presented in figure 8, based on Fick's laws of diffusion, measures moisture diffusion rates by analyzing the vapour pressure gradient across materials, offering highly precise results for uniform materials. However, it is challenging to apply to anisotropic materials like wood, which exhibit variable moisture permeability in different grain directions, necessitating precise humidity control that complicates laboratory execution [48,77].

The gravimetric cup method, standardized by ISO 12572 and ASTM E96M, is the most widely accepted technique for measuring water vapour diffusion resistivity. It involves sealing a material specimen between two environments with different relative humidity levels, with the wet cup method inducing outward vapour flux from a chamber containing distilled water (RH ≈ 100%) and the dry cup method creating inward flux using a desiccant (RH ≈ 0%) see Figure 9,10 for an illustration of the cup method [40,54,62,74].

Figure 9: Illustration of Gravemtric Method (Olaoye and Dewsbury, 2018)

Figure 10: Shelving in the interior of test room at UTAS, Australia

Despite being the standard for timber testing, the gravimetric method traditionally assumes a single humidity level, limiting its ability to replicate real-world environmental fluctuations. To address this, recent enhancements incorporate multi-RH testing to improve accuracy for hygrothermal modeling, particularly in building envelope applications [5,64].

Laboratory tests, while useful, may not fully replicate real-world moisture interactions in buildings, necessitating empirical validation through full-scale test walls as demonstrated in Figure 11, which monitor moisture transport in timber assemblies under natural climate conditions using embedded sensors [38]. While test-wall validation is essential for refining hygrothermal simulation models, it requires long-term monitoring and significant setup costs. Among these methodologies, the gravimetric cup method with enhanced multi-RH testing emerges as the most suitable approach for determining the water vapour diffusion resistivity of solid wood and CLT products, as it aligns with internationally recognized standards while allowing for improved simulation-based moisture risk assessments [34,69].

Figure 11: Image or diagram of test wall

5- Results and Discussion

Accurately quantifying the water vapour diffusion resistivity of construction materials is essential for evaluating their simulation based hygrothermal performance under various conditions. Each method's

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unique strengths and limitations are critiqued in this section. Table 1 shows a summary of advantages and disadvantages of each method. Some key considerations come into effect when each of the six methods is examined within the context of establishing the water vapour diffusion resistivity properties for solid wood, solid wood based engineered wood products that both reflect the conditions for the exterior environment and have suitable data for hygrothermal simulation.

Table 1: Measuring Water Vapout Diffusion Methods

Method	Advantages	Limitations
Electronic-analytical method	Rapid measurements, high automation.	May not effectively simulate real-world fluctuating vapour pressure conditions caused by environmental humidity changes [71].
Sweating guarded hot plate method	Suitable for testing how textiles manage heat and moisture.	Limited to conditions resembling human skin, less suitable for construction materials in exterior environmental conditions[32,85].
Dynamic moisture permeation cell (DMPC) method	Precise control over test conditions, can simulate various environmental scenarios.	Complexity and cost may be prohibitive for routine quality control, more suited to laboratory environments than production lines or field testing [27].
Isothermal method	Provides precise information about material behaviour under specific humidity conditions.	Time-intensive to reach equilibrium moisture content at each humidity level; requires precise environmental control, making setup and maintenance complex and costly [2,3].
Vapour pressure method	Effective in assessing material performance against moisture, crucial for preventing condensation and mould growth.	Requires maintaining precise humidity control during tests and considering the material's anisotropic nature, limiting this method's application due to costly experimental processes [48].
Gravimetric method	Provides crucial data on moisture handling properties under various humidity levels.	Time-consuming due to equilibrium moisture content variations; requires meticulous environmental control for accurate results [54,69]. The current international standard is significantly limited by its single temperature and relative humidity methodology [15].
Enhanced gravimetric method	Testing materials under different relative humidity conditions to establish relative humidity dependent water vapour diffusion resistivity values. This better reflects real world conditions that a building envelope experiences.	Only evaluates materials at a single temperature.[30,32,63,64].

The electronic-analytical, sweating guarded hot plate methods may provide a water vapour diffusion value but their application to construction materials may be somewhat compromised. Dynamic moisture permeation cell and Isothermal methods allow for testing under different laboratory based environmental conditions, however the laboratory establishment and operation can be complex and costly. The vapour pressure method focuses on establishing when condensation may occur, whereas hygrothermal simulation focuses on moisture diffusion and when combined with bio-hygrothermal simulation explores mould growth risk. It is well accepted that mould growth risk occurs when the relative humidity is above 60% in interstitial spaces, making this method less appropriate.

The gravimetric method is widely used and supported by international standards. But as noted in the table, it is somewhat limited by the single temperature and single humidity test set points that do not resemble the conditions often experienced by materials in a building envelope. The development of the enhanced gravimetric method has gained significant traction in the last decade. Initially from a criticism of the gravimetric method limitations and increasingly by the need for simulation tools to accurate calculate moisture and heat diffusion and mould growth risks through the dynamic environment experienced by the various components that exist in a building envelope system. The enhanced gravimetric method still requires significant technical application for the control and operation of the test room and the measurement processes. However, Olaoye who questioned the gravimetric method repurposed an existing test building and completed an evaluation of water vapour diffusion resistivity for five weather resistive pliable membranes under different relative humidity conditions [65]. In that same research Olaoye identified that the final simulation results varied significantly between water vapour diffusion resistivity values obtained from the single-point and multi-point test methods [65].

Lepage (2012) [46] in tegrated the gravimetric method and empirical testing with advanced transient simulation tools to empirically validate water vapour diffusions resistivity properties. This hybrid approach combines the strengths of direct measurement and dynamic simulation, enabling a comprehensive analysis of material performance under varying environmental conditions. By incorporating both empirical data and simulations, this methodology enhances the accuracy of predictions regarding moisture behaviour in construction materials, providing a robust framework for evaluating water vapour diffusion resistivity.

The enhanced gravimetric method appears to be the most appropriate method to quantify the water vapour diffusion properties of Australian plantation solid wood and solid wood-based EWP's commonly used to construct building envelope systems.

This study will employ the enhanced gravimetric method and the test wall emthod. This will generate accurate moisture diffusion resistivity data for Australian plantation-grown timber, and provide a platform to compare transient hygrothermal simulation resulst to a real-life timber based external wall system, contributing to moisture management strategies in sustainable timber construction.

4. Conclusion

Accurate water vapour diffusion resistivity properties are essential for high-quality transient hygrothermal simulations of building envelope systems for both design and forensic analysis reasons. This research has identified a significant lack of empirical data for the water vapour diffusion resistivity of Australian-grown plantation softwood and hardwood sold timber and solid wood based engineered wood products. This critical gap in knowledge may significantly impact the accuracy of hygrothermal simulation results.

This research sought to identify the most appropriate method to quantify the water vapour diffusion resistivity properties of Australian plantation grown hardwood and softwood solid wood products that are commonly used to manufacture engineered wood products. The analysis established that there are six accepted methods to establish the water vapour diffusion resistivity.

The research identified that the gravimetric test method as described in ISO12572 is the most common method in use by industry and researchers in the northern hemisphere to establish the water vapour diffusion resistivity properties of construction materials. But the research also identified that this method may be inadequate due to its single temperature and relative humidity measurement process. This has led to the development and application of the enhanced gravimetric method which evaluates the water vapour diffusion resistivity properties under different relative humidity conditions, which will be adopted in this research [34]. It should also be noted that all methods referred to calibration and empirical validation, where materials are measured in a detailed manner within a test-wall exposed to the exterior environment [46]. This aspect will also be explored in this research.

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