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Towards a Standardized Moisture Content Classification for Timber Defect Assessment: A Review and Framework for Condition-Based Maintenance

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Abstract

Moisture content is a critical parameter influencing the durability, structural performance, and maintenance of timber structures. However, current building inspection practices often rely on subjective interpretation, resulting in inconsistent assessment outcomes and ineffective maintenance decision-making. Despite the availability of various moisture measurement techniques, a standardized framework for interpreting moisture levels in relation to timber condition is still lacking. This study presents a structured review and synthesis of moisture content thresholds reported in the literature and proposes a standardized classification framework for timber defect assessment. The findings indicate that moisture content levels can be systematically categorized into four condition states dry, moderate, poor, and critical for each associated with specific maintenance actions. The proposed framework provides a practical linkage between moisture measurements and condition-based maintenance strategies, enabling more consistent and reliable inspection practices. The study contributes by transforming dispersed moisture-related data into a unified and actionable classification system, serving as a decision-support tool for building inspectors and maintenance practitioners. The proposed framework enhances the implementation of condition-based maintenance by reducing subjectivity and improving the accuracy of timber condition assessment.

Keywords: moisture contents; condition based maintenance; maintenance; defect; timber

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1.0. Introduction

Timber has been one of the most widely used construction materials throughout human history, valued for its abundance, workability, high strength to weight ratio, and aesthetic qualities. According to (Bach & Hildebrand, 2018), timber also possesses significant carbon sequestration capacity, making it a sustainable building material that supports green initiatives in the construction industry. In addition, timber offers advantages in terms of rapid installation, lower construction costs, and good thermal performance (Green & Taggart, 2020). These characteristics have contributed to its continued application in modern construction, particularly in the context of sustainable building development.

However, the longevity and structural integrity of timber structures are highly dependent on their ability to withstand environmental stressors, particularly moisture. Prolonged exposure to elevated moisture levels can lead to material degradation, including fungal decay, dimensional

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instability, and loss of structural strength, which ultimately compromise building performance and safety (Lima et al., 2022; Brischke & Meyer, 2015). Furthermore, timber construction requires careful monitoring of defects, as any deterioration may significantly affect the durability and serviceability of the structure (Ayanleye et al., 2022).

Despite the critical role of moisture in influencing timber performance, current maintenance practices in buildings often rely on visual inspections and subjective judgment, which may not accurately represent the actual condition of timber elements (Ahmad et al., 2018). The absence of a standardized assessment framework frequently results in inconsistent inspection outcomes and unreliable condition evaluations, thereby limiting the effectiveness of maintenance decision making processes (Jones & Sharp, 2007). This issue is particularly significant within the context of Condition-Based Maintenance (CBM), where maintenance actions should be guided by measurable and objective condition data.

In response to these challenges, the development of a standardized moisture rating scale is essential to translate moisture content measurements into meaningful condition classifications. Such a scale enhances CBM by establishing a direct linkage between measured moisture levels and corresponding maintenance actions. Instead of relying on subjective interpretation, inspectors are able to classify timber conditions based on predefined thresholds, thereby improving the consistency of inspection reporting and reducing variability among assessors.

Moreover, the use of a structured rating system increases the accuracy of condition assessment by enabling early detection of moisture related defects before they progress into more severe structural issues. From a maintenance perspective, this approach improves efficiency in maintenance planning, as building managers can prioritise interventions based on the severity of the condition identified. In addition, the rating scale functions as a decision support tool that facilitates systematic prioritisation of maintenance activities, ultimately strengthening the implementation of CBM and contributing to enhanced building performance, extended service life, and reduced lifecycle costs (Mobley, 2002; ISO 17359, 2018).

2.0. Moisture Contents in Timber Structure

Moisture content is a significant factor contributing to building defects, particularly in structures that incorporate wood as a primary material. Numerous studies have highlighted that high moisture levels in timber components can accelerate biological deterioration processes such as fungal decay and insect infestation, leading to structural weaknesses (Isa et al., 2021). Timber is a hygroscopic material, meaning it naturally absorbs and releases moisture in response to environmental conditions. When exposed to high humidity or direct moisture ingress, timber can swell, warp, and ultimately lose its structural integrity. Prolonged exposure can also promote mold growth and rot, which not only compromises the durability of the building but also poses health risks to occupants. As a result, monitoring and controlling moisture content is critical in the maintenance and longevity of wooden structures.

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Figure 1. Leaky Wood Surfaces.

Moisture content plays a critical role in the deterioration of timber structures. As moisture penetrates the wood surface, it gradually seeps into the inner layers, leading to decay that compromises the wood's structural and tactile properties often making it feel soft to the touch (Isa et al., 2021). As the moisture level increases, damage becomes more pronounced, accelerating biological degradation such as fungal attack and ultimately leading to structural failure. Excessive moisture can cause widespread decay, severely weakening timber elements and potentially resulting in partial or total structural collapse. According to (Abdoli et al., 2024), assessing moisture content is a vital part of preliminary investigations during visual nspections, as it provides early indications of potential structural issues in timber components. Wood moisture content is widely regarded as the main driver of biological degradation, given that fungal activity typically requires a minimum of 20% moisture (Lima et al., 2022). The objectives of this study are to review results of several research works are presented and analyzed regarding the differences level of moisture contents. This information can provide the data to building inspection about timber performance on moisture content. Moreover, recommendations for future research are included attending to the conclusions drawn from the analysed literature.

Figure 2. Various Assessment Moisture Contents Inspection.

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Figure 3. Moisture Contents Inspection.

2.1. Structural Effects of Moisture Content in Timber

Moisture content plays a decisive role in determining the performance and durability of timber structures. Variations in moisture not only influence the physical characteristics of wood but also its structural and mechanical properties. Among the most critical consequences are the reduction of strength and stiffness, dimensional instability, and the weakening of joints, all of which can compromise structural integrity over time.

2.1.1. Reduced Strength and Stiffness

The mechanical properties of timber, particularly strength and stiffness, are highly sensitive to moisture variations. When wood absorbs water, especially below the fibre saturation point (FSP), the bound water within the cell walls disrupts intermolecular hydrogen bonds, leading to a significant decline in mechanical performance (Glass & Zelinka, 2021).

This reduction in stiffness has important implications for serviceability. Timber elements with elevated moisture levels often exhibit excessive deflections under load before reaching ultimate failure, posing a risk for long-term structural safety (Cai et al., 2021). In engineered wood products such as glued laminated timber (glulam), cyclic fluctuations in moisture accelerate creep deformation and reduce load-bearing capacity (Lanata, 2015). These findings highlight the importance of maintaining timber moisture within safe limits to preserve its strength and stiffness.

2.1.2. Dimensional Instability

Wood is an anisotropic material, meaning that its properties vary with direction. Its hygroscopic nature, i.e. its ability to absorb and release moisture, causes wood to change size (expand or shrink) significantly when air humidity changes, making it dimensionally unstable when exposed to varying humidity (Jakob et al., 2022). Dimensional instability not only affects aesthetics but also contributes to the development of internal stresses that may cause surface checking, honeycombing, and splits (Udele et al., 2021). These defects reduce the effective cross-sectional area of timber and accelerate mechanical degradation. In building applications, such instability undermines the performance of flooring, cladding, and structural panels, especially when exposed to cyclic wetting and drying conditions.

2.1.3. Joint Weakness

The performance of timber joints is particularly vulnerable to changes in moisture content, as dimensional movements and stress redistribution affect the integrity of connections. Moisture fluctuations cause differential movement between connected members, leading to loosened fittings, reduced frictional resistance, and localized stress concentrations (Ji et al., 2023).

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2.2. Durability and Biological Effects of Moisture in Timber

The durability of timber is closely linked to its interaction with moisture, which plays a critical role in enabling biological degradation. High moisture content will accelerate wood damage with fungal attack, insect attack and mold growth. These biological effects compromise the long-term serviceability and safety of timber structures, particularly in humid climates or environments where protective measures are inadequate.

2.2.1. Decay and Fungi

Fungal decay is among the most severe durability challenges faced by timber. Wood decay fungi require sufficient moisture, oxygen, and favorable temperature conditions to colonize and degrade wood cell walls. The critical threshold for fungal activity is generally around 20% moisture content (Y. Wang et al., 2022).

2.2.2. Insect Infestation

Insect attack represents another major biological hazard, strongly influenced by moisture content. Termites, carpenter ants, and beetles are particularly destructive when timber maintains elevated moisture levels. Termites thrive in damp environments, using softened wood as both habitat and food source, often leading to extensive hidden damage in structural elements (Khan & Ahmad, 2018). Moisture not only facilitates insect colonization but also accelerates the rate of damage. For instance, subterranean termites exhibit higher activity in timber with moisture contents exceeding 25%, where softened fibers enhance tunneling efficiency (Kalleshwaraswamy et al., 2022).

The structural effects of moisture content in timber are multifaceted and interdependent. Reduced strength and stiffness undermine the material's capacity to resist loads, while dimensional instability induces geometric distortions that accelerate deterioration. Furthermore, joint weakness caused by both adhesive degradation and mechanical loosening exacerbates structural vulnerabilities.

Decay fungi cause profound reductions in mechanical strength, often preceding visible signs of damage. Insects such as termites and beetles exploit moist conditions to colonize and weaken timber elements, while mold growth degrades surfaces and exacerbates moisture retention, indirectly facilitating further biological attack. Collectively, these processes highlight the central role of moisture management in prolonging the service life of timber structures. Preventive strategies such as chemical treatments, protective coatings, design detailing to minimize water ingress, and proper ventilation are essential to safeguarding timber against biological deterioration.

3.0. Moisture Control Strategies

Moisture content (MC) monitoring is essential for ensuring the durability and structural safety of timber, as excessive or fluctuating moisture promotes mechanical weakening, dimensional instability, and biological deterioration. Since timber is hygroscopic, it continuously exchanges moisture with its environment; thus, monitoring systems and control strategies are required to maintain MC within safe thresholds, typically below the fibre saturation point (≈30%) and preferably within the 8–15% range for most service conditions (Glass & Zelinka, 2021).

Visual inspection is the fundamental and widely used for Non-Destructive Testing (NDT) techniques for assessing the condition of wood. Visual inspection is widely used in structural maintenance due to its simplicity, low cost, and the immediacy of results, requiring no special equipment or expertise (Brinker et al., 2020). Visual inspection maintenance has been proposed before maintenance program to collect and evaluate data defects in parametric inspection (Faqih & Zayed, 2021; Mohamad Haszirul Mohd Hashim, 2021). This evaluation inspection based on standard specification and action will be taken to achieve the standard set (Awasho & Alemu, 2023). This method is important for collecting information for maintenance management and action will be taken after an inspection process and no action will be taken if it is in good condition (S. M. H. M. Hashim

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& Ghani, 2017). (Wanigarathna et al., 2019) argues that the approach taken to the condition-based maintenance to existing building can maintain or improve from the original condition.

However, visual inspection is inherently subjective and limited to surface defects, offering no insight into hidden moisture or internal deterioration in wooden elements (Bahrami et al., 2025). It highlighted by (Ghani et al., 2023; M. H. M. Hashim et al., 2022) in building maintenance, particularly in timber structures, the effectiveness of inspections heavily depends on accurate interpretation of visible signs and material conditions. Misinterpretation or oversight of critical issues related to moisture content can lead to inaccurate diagnoses of structural components (Ghani et al., 2023). This not only compromises the reliability of visual inspections but also increases the risk of undetected deterioration, ultimately affecting the structural integrity, safety, and service life of the building (M. H. M. Hashim et al., 2022). Without proper understanding of how varying moisture levels influence timber performance, maintenance decisions may be delayed or ineffective, leading to higher repair costs and safety hazards.

This review is based on an extensive analysis of literature, including reference books, magazines, journal articles, conference papers, and technical reports. A structured approach was adopted to examine the current state of moisture content monitoring techniques in the maintenance of timber structures. Relevant literature was systematically identified through comprehensive searches in established academic databases such as Scopus, ScienceDirect, Web of Science, and Google Scholar, using keywords including “moisture content in wood,” “wooden structure monitoring,” “non-destructive testing for timber,” and “moisture assessment in wood.”

In addition, technical reports, building standards (such as ASTM and ISO), and industry white papers were reviewed to incorporate both academic and practical perspectives. Methods related to building inspection and defect assessment were also critically analysed, including approaches developed and applied by previous researchers. Furthermore, British and Australian standards were examined to provide guidance on maintenance management design.

The primary objective of this study is to identify and evaluate the levels of moisture content assessment in timber. Through a comparative synthesis, this review highlights current best practices, identifies technological gaps, and explores emerging trends in moisture monitoring. The findings provide a valuable reference for researchers, engineers, and conservation professionals involved in timber structure maintenance. Moreover, the proposed classification and framework offer practical guidance for building inspectors and maintenance practitioners, enhancing consistency in assessment and supporting more effective condition-based maintenance strategies.

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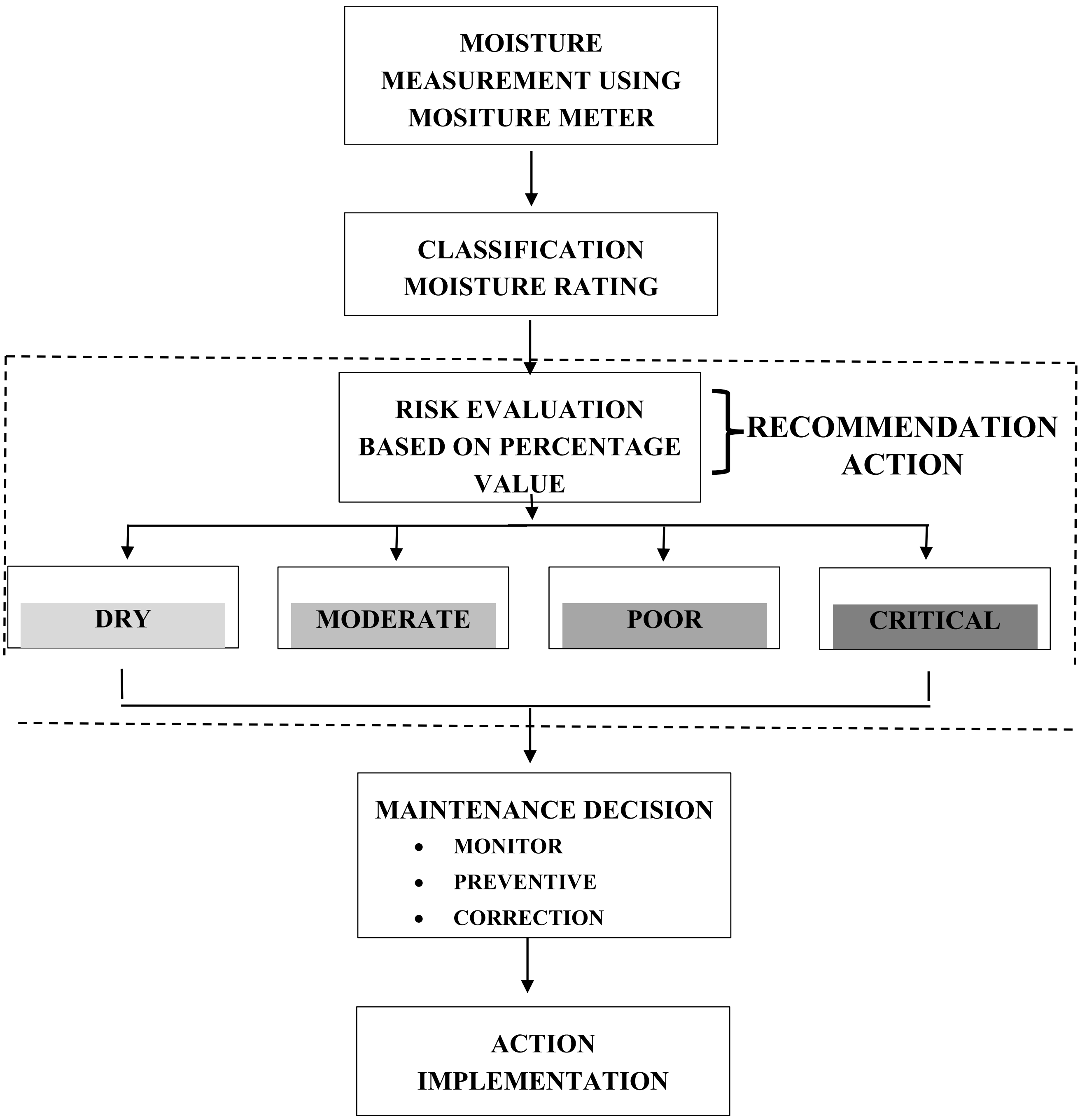

Flowchart 1. Moisture Based Timber Condition Assessment Framework.

4.0. Moisture Content Measurements and Prediction

Moisture content is measured based on the percentage of moisture present on the surface of the structure. According to (López et al., 2023), the acceptable moisture content is between 8% and 20%. This is because moisture content of 10% to 18% still has high flexural strength (Bukauskas et al., 2019). However, (Brougui et al., 2025) states that the appropriate level for wood strength is between 8% and 12%. At a moisture index below 10%, termite attacks can be avoided (Ghani et al., 2023). However, (Gwynne, 2025) states that fungal growth will not occur when the humidity is less than 10%. However, (Riccadonna & others, 2021) states that the range of moisture content is between 12% and 22%.

According to (Deuse & others, 2017) good moisture conditions are when the percentage is below 5% but (Sola-Caraballo et al., 2022) make a good assessment of the moisture content at 8%. This has also been supported by (Kherais et al., 2024) that the maximum strength of wood is between 4% to

8%. It can be considered that the dry state of wood is between 6% to 8% (Agu et al., 2021). This 6% moisture content has a parallel and compressive shape elasticity in the modulus of elasticity (MOE) test (Emmerich & Brischke, 2023). Moisture containing cellulose can attract termites but will not attack if the moisture content is below 8% (Marais et al., 2022). (Mainey et al., 2020) stated that a good moisture content is between 9% and 15%.

Testing by (Emmerich & Brischke, 2023) on the strength of plywood samples cut with dimensions of 500mm x 500mm x 2mm and having 3 layers of panels with 6mm thickness. The durability test found that the best results were a moisture content of 4-6% which had a bending of 58.10 N/mm². When the moisture content was at 10-12% the bending was at 55.70 N/mm². Finally, a moisture content of 16-18% had a bending of 53.20 N/mm². In a study conducted by (Ensminger & Bond, 2024) on a 20mm thick wooden board, the thickness change over a period of 30 days was shown in Figure 4.

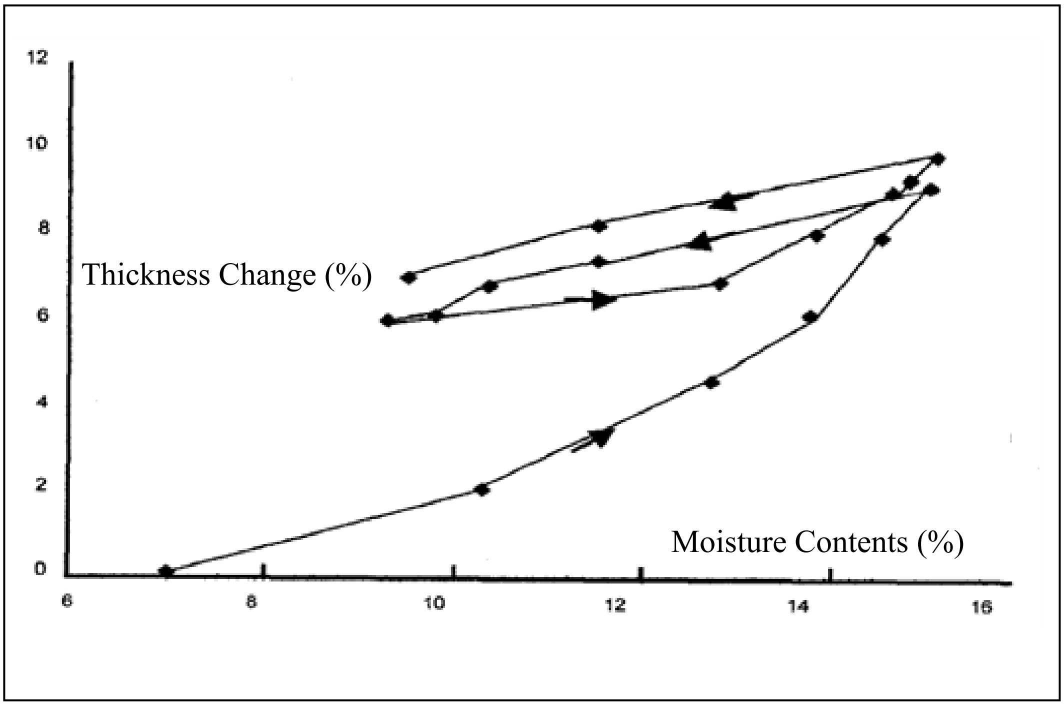

Figure 4. Changes in Wood Properties (Ensminger & Bond, 2024).

The structural condition is good when the moisture content is at 12% to 15% because it provides higher strength (Söügütlü et al., 2016). This is because moisture at 12% can prevent the formation of biological degradation by fungi or termite attacks (Henriques, 2017). (S. Wang, 2024) also stated that the construction of suitable wooden structures in construction is between 12% and not more than 14% because it will have long-term effects such as structural failure.

Wood that will be used in a dry state is a moisture content below 15% (Zoormand, 2024). This is because (Association & others, 2024) classifies when the moisture content is 12% to 15% as a closed surface that is not exposed to the outside weather. The category of wood is strong, hard and heavy when the moisture content is not more than 15% (Rahmon & Jimoh, 2020). However, (Thybring et al., 2022) states that the strength of wood will begin to be lost when the moisture content starts from 12% to 15% and will suffer damage when the moisture content exceeds 15% (De Silva & Liyanage, 2019). This is because the structural durability cannot be ignored if the moisture content exceeds 16% (Riggio et al., 2015). This is also supported by (Seidu et al., 2019) where the surface at risk is between 17% to below 20%. This is illustrated in Figure 5 namely the strength and elasticity that will decrease when the moisture content is high.

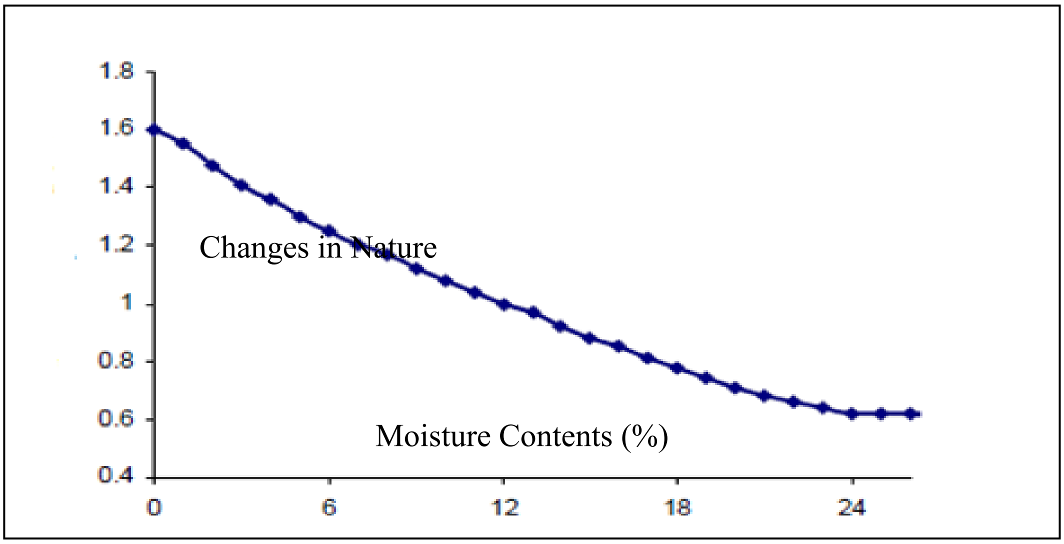

Figure 5. Effect of Moisture Content on Changes in Mechanical Properties (Lear, 2006).

When the humidity exceeds 20% (Thybring et al., 2022) states that the structure has been exposed to a wet surface. Humidity of 20% to 22% is a condition that is suitable for fungal growth (Parnham & Russen, 2022) and rot (Arriaga et al., 2023). This is supported by (Henriques, 2017) at fungal attack can be prevented if the moisture content is below 20%. The percentage of dry moisture content if it is at or below 19% (Govorushko, 2019). Structures are considered safe from fungal decay if the moisture content is 20% or lower (Lima et al., 2022). This is because termite infestation occurs at a moisture content of 20% to 30% in wood structures (Govorushko, 2019) or can destroy the structure (Marais et al., 2022).

5.0. Results and Discussion

The findings highlight that moisture content is a critical parameter influencing the performance, durability, and maintenance of timber structures. The reviewed literature consistently indicates that acceptable moisture content for timber generally ranges between 8% and 20%, within which the material can still maintain its functional performance. In particular, moisture levels between 10% and 18% demonstrate relatively high flexural strength, indicating that timber remains structurally reliable under these conditions. Lower moisture content, especially within the range of 4% to 12%, contributes to improved mechanical properties such as stiffness and elasticity, with optimal performance typically observed between 6% and 8%, representing dry and stable conditions.

Conversely, increasing moisture content significantly elevates the risk of biological deterioration. Moisture levels above 12% mark the onset of potential degradation, while values exceeding 20% are strongly associated with fungal growth and long-term structural damage. In addition, maintaining moisture content below 10% is effective in minimizing the risk of termite infestation and inhibiting fungal activity. These findings confirm that moisture thresholds are closely linked to timber condition and can serve as a reliable indicator for assessing structural integrity.

The integration of a moisture content rating scale into condition-based maintenance (CBM) is identified as a significant advancement in timber maintenance practices. By transforming raw moisture data into actionable insights, the proposed framework reduces uncertainty in inspection and decision-making processes. This approach aligns with predictive maintenance principles, where early detection of deterioration enables timely intervention, thereby preventing costly repairs and structural failures.

However, the analysis also reveals inconsistencies in defining acceptable and optimal moisture ranges across different studies, which creates challenges in interpreting inspection data. The absence of a standardized classification system often leads to subjective assessments, where similar moisture readings may result in different maintenance decisions depending on the inspector's experience. Furthermore, environmental factors such as temperature and humidity can influence moisture behaviour, indicating the need for further validation through field-based studies.

Therefore, the study emphasizes the necessity of developing a structured moisture content classification framework that categorizes timber conditions into clearly defined levels. Such a framework would enhance the consistency and reliability of building inspections, support effective implementation of condition-based maintenance strategies, and improve decision-making by directly linking moisture levels to appropriate maintenance actions.

6.0. Proposed Moisture Content Rating Scale

Based on the synthesis, a standardized moisture content rating scale is proposed to classify timber conditions into four levels: dry, moderate, poor, and critical. Each classification is directly associated with a specific maintenance strategy, enabling a clear linkage between moisture levels and appropriate actions. This structured approach enhances condition-based maintenance by transforming moisture data into practical decision-making guidance. Furthermore, the high level of agreement reported in previous studies supports the reliability and applicability of the proposed classification framework.

Moisture Content (%)	Condition Level	Maintenance Strategy
< 12%	Dry	No immediate maintenance required
12% – 20%	Moderate	Monitoring and preventive maintenance
20% – 25%	Poor	Repair and moisture control actions
> 25%	Critical	Urgent repair or replacement

7.0. Conclusions

This review confirms that moisture content is a fundamental parameter in assessing the condition, durability, and structural performance of timber. Although various moisture measurement techniques both destructive and non-destructive are widely available and essential for detecting defects, their practical application in condition based maintenance remains limited due to the absence of a standardized classification framework. Moisture content monitoring is crucial, as excessive or fluctuating levels contribute to mechanical weakening, dimensional instability, and biological deterioration such as fungal decay and termite attack.

The findings indicate that timber performance is strongly influenced by moisture levels, which range from as low as 4% to as high as 22% in the literature. Moisture content between 8% and 15% is generally associated with higher structural strength, while levels around 12% are effective in minimizing biological degradation. In addition, visual inspection methods remain an important non-invasive approach for identifying surface defects, decay, and general deterioration in existing timber structures, supporting overall condition assessment.

To address existing gaps, this study proposes a standardized moisture content rating scale that classifies timber conditions into four levels: dry, moderate, poor, and critical. Each classification is directly linked to appropriate maintenance actions, enabling more systematic, consistent, and reliable decision-making during building inspections. This framework effectively bridges the gap between moisture measurement and maintenance practices, transforming raw data into actionable insights for inspectors.

Overall, the study emphasizes that moisture content defect assessment is a vital tool in ensuring the safety, durability, and sustainability of timber structures. Future research should focus on empirical validation of the proposed framework and its integration with environmental monitoring systems to enhance its applicability and accuracy in real-world conditions.

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