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THE WOOD MOISTURE FACTOR ON THE BIOLOGICAL DETERIORATION OF WOODEN STRUCTURES

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ABSTRACT

With sustainability as a growing concern, the rehabilitation of buildings arises as one of the main forms of support for the construction sector. Rehabilitation, in comparison with new construction, is seen as a path to minimize the negative impacts of this activity by reducing, for example, the energy consumption of buildings and its consequent impact on energy production (still meeting the current needs for comfort) and the extraction of raw materials. Wood has a high potential for numerous purposes, also, it is a natural, renewable, and sustainable resource, presenting itself as a promising construction material with enormous importance for the bio-based economy. However, despite being a traditional material, reliable service life prediction of wooden structures continues to be a challenge. Like other biobased materials, wood can be subject to biological deterioration by fungi and insects. The biological agents, when combined with favourable conditions (e.g., temperature, air relative humidity, wood moisture content, etc.), can lead to simply aesthetic damage, reduction in indoor air quality, or compromising its resistant load capacity, creating a risk to human health and safety, in addition to an increase of repair and maintenance costs. Many approaches consider wood moisture content as the key factor to control the activation of the decay process, since fungal colonization of wood requires a minimum moisture content of around 20%. Moreover, though subterranean termites (one of the most damaging wood insects) are able to infest dry wood, contact to moisture is fundamental for effective installation of the colonies. This paper addresses moisture as a conditioning factor in the degradation of wood in construction. The role of water on the development of the biodeterioration processes, the transport of water within wooden elements, as well as how the current normative references address the issue are discussed. Finally, this work presents some of the exiting methods for continuous moisture content monitoring systems that, associated with regular maintenance, can be an alternative to chemical treatments, increasingly limited due to current environmental legislation.

KEYWORDS: Wooden structures; Moisture content; Monitoring; Biological deterioration.

1. INTRODUCTION

Wood is one of the oldest building materials used by mankind, with several reports of historical discoveries of its use in distant times. An example are the timber-frame wells with an age over than 7000 years found in Germany, which is considered the oldest report on the use of wood as a structural material [1]. However, the emergence of new construction materials, such as concrete and steel, led to loss of market competitiveness of wood, driving to a strong abandonment of it.

Currently, the construction sector is responsible for consuming 40% of all primary energy and 40% of raw materials, 36% of greenhouse gases (GHG) emissions, and generating 33% of all residues [2]. Thus, in order to achieve the goals established by the EU climate action & Green Deal (reduction of GHG emissions by 55% until 2030 and making the EU climate-neutral by 2050 [3]), there was strong growth in the use of biomaterials and the number of building rehabilitations.

This growth in sustainable awareness, the development of new Engineered Wood Products (EWP), and the commitment to rehabilitation as a path to reduce the energy consumption of buildings, the consumption of materials, the generation of waste, and the increase of buildings service life resulted in the resurgence of wood as a construction material for structural use.

Like other organic materials, wood is susceptible to biological deterioration (fungi and insects) in addition to physical and chemical (e.g. fire and weathering), and despite being a traditional building material, the durability of wooden structures remains a challenge for engineers and architects. In order to start the process of biological degradation, it is necessary to combine, simultaneously and for a certain period, a series of factors. For example, although there are several fungi that cause wood decay with different growth needs and characteristics, in general, an adequate amount of oxygen, elevated moisture content of the wood, and favorable environmental conditions (temperature and relative humidity of the air) are fundamental for fungal infection and development [4].

Among the biological degradation agents of wood, subterranean termites and fungi are accepted as the most relevant. Subterranean termites degrade wood by typically establishing underground nests on dead wood debris and building galleries of moist soil and fecal particles in order to reach other wood resources [5]. Among the fungi, molds and sapstain fungi are not able to metabolize structural components in relevant levels, but their presence is directly responsible for risks to human health (e.g. respiratory problems) and aesthetic damage [6]. On the other hand, decay fungi are able to degrade the lignin and cellulose components, causing mass loss and reducing the wood mechanical properties [6].

Thus, biological deterioration can be responsible for severe structural damage to wood, a risk to human health, reduction of the building's service life, and also high costs with rehabilitation actions [5]. For example, it was estimated that losses caused by subterranean termites alone in Australia are around 1.5 billion US dollars per year [7].

Among these deterioration agents, one of the common factors for the process to start is the presence of elevated moisture in wood. Molds and sapstain fungi are able to growth at relatively low levels close to 20%, decay fungi have a variety of moisture requirements with the optimum moisture content for decay in the range between 50% and 100% [6]) and subterranean termites, despite being able to attack wood with lower moisture contents, prefer wood with moisture content above 20% [4].

For this reason, several approaches consider that controlling the moisture content and keeping the wood dry is the most effective way to protect wood from biological degradation [8], leading to investments in continuous monitoring of the moisture content, combined with periodic maintenance as an alternative to chemical treatments, increasingly limited due to restrictive regulations [9, 10].

Finally, considering the service life fundamental to maximize the benefits of rehabilitation and the use of wood as a structural construction material, one should consider the biological deterioration process and the main factors responsible for its occurrence, such as moisture dynamics.

2. WOOD MOISTURE CONTENT AND MONITORING SYSTEMS

The moisture content has impacts on most of physical and mechanical properties of wood, manly through conditioning dimensional changes, development of cracks, fungal decay, and insect attacks. It is usually expressed in terms of its mass (water mass in relation to the wood mass) [11]. Moisture is present in wood in three distinct forms: combined water, water of imbibition, and free water. Combined water is linked to the wood by powerful chemical forces, and it is removable only by the chemical decomposition of the material, while water of imbibition is bounded to the cell wall by intermolecular attractive forces, and its release causes dimensional changes (shrinkage) on the wood. On the other hand, free water is located inside the cell cavities (lumen) in the form of liquid and water vapor [4].

Immediately after the tree is felled, the wood starts to lose its free water (in this phase the moisture content is usually above 100%). When the wood loses all its free water, but the cell walls are still completely saturated with bound water, it is said that the fiber saturation point (FSP) has been reached (around 25%-30%). The fiber saturation state can be reached only theoretically, since the adsorption and desorption process are temporarily and spatially ongoing processes [8]. The FSP is considered a threshold, for lower moisture contents the drying process will lead to shrinkage in wood and affect mechanical properties [12].

Wood, as a natural and hygroscopic material, absorbs and releases moisture according to the environmental conditions in which it is inserted (temperature and relative humidity of the air), continuously seeking to reach its equilibrium moisture content (EMC) [5], and its hygroscopic behavior turns possible to estimate overall moisture content values, associating hygrometric equilibrium curves, temperature, and air relative humidity data [4]. For example, according to its hygrometric equilibrium curve, the EMC of maritime pine on conditions around 20 ºC and 65% of relative humidity of air is 12% [4].

The moisture content can be measured by direct or indirect methods. The first, according to the standard EN 13183 [11], is based on gravimetric measurements before and after oven-drying and it is the most used in laboratory evaluations. Within the indirect methods, a full range of techniques are available to estimate the moisture content, for example, the electrical resistance, capacitive, microwave, among other methods [13]. Although being less accurate, the indirect methods are usually preferred to in situ measurements, mainly due to its practicality, semi/non-destructive assessment, and versatility. Moreover, it is also commonly used for continuous monitoring of timber structures, automatically acquiring, and storing data periodically through data loggers. Figure 1 presents a schematic of the most common methods for measuring the moisture content.

Among the indirect methods, obtaining the moisture content from electrical resistance is the most widespread. This method is based on the electrical resistance/conductibility property of wood, where higher levels of moisture content reduce the wood electrical resistance [14]. The moisture content value is obtained from the conversion of electrical resistance using calibration curves found in the literature, as an example in [15], which correlates wood temperature, electrical resistance, and moisture content. Nowadays, there are types of equipment capable of performing the conversion automatically. In practical terms, two metal pins are inserted at the depth which the moisture content is to be obtained, and the pins are connected to the measuring equipment. Figure 2 shows an example of equipment capable of measuring the moisture content through the electrical resistance method. In one of the figures, it is possible to notice the presence of molds in the wood with 26.3% moisture content, aligning with the moisture content threshold for molds to appear, exposed in section 1.

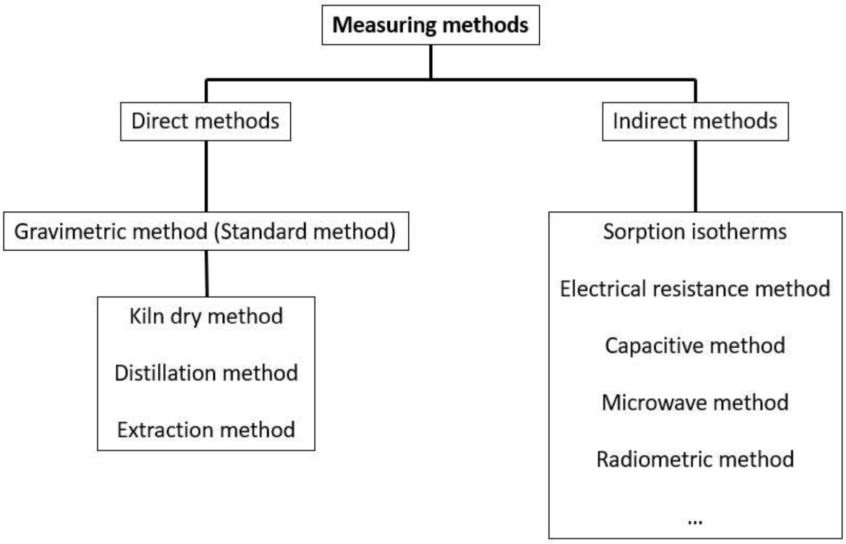

Figure 1: Overview of the most common methods for measuring the wood moisture content, adapted from [14].

Figure 2: Measurements of the surface moisture content of wood using the electrical resistance method.

Due to its accuracy, practicality, and flexibility, this method is the most used in the continuous monitoring of wooden structures, where several techniques have been developed (e.g. [16]). Despite the recognized accuracy of the method, it makes only local measurements, implying the accurate identification of the measurement points, taking into account the areas of higher humidification risk, and the need for a compromise between redundancy and diversity in data (e.g. having comparable measurements and analyzing different locations) [17].

Continuous monitoring of hygrothermal data (moisture content, temperature, and relative air humidity) is extremely relevant for the durability of wooden structures. The data obtained from the measurements can be used in biological degradation models (e.g. [18]), enabling to estimate the service life of buildings and serving as a basis for decision making in maintenance plans and rehabilitation works. However, [19] warns that, although durability has been investigated at the material level, few researchers have investigated the prediction of decay in structural components. In addition, existing models are geared towards decay caused by fungi, but complete and adaptable models for deterioration caused by insects are still limited.

3. EUROPEAN DURABILITY STANDARDS

In the case of European standards, the durability of wooden structures is addressed in the form of natural durability of the species, treatability, and exposure conditions. Natural durability is defined as the natural resistance of a timber species against degradation agents (fungi and insects) [5] and varies according to species, geographic location, and trunk region (sapwood or heartwood) [20].

Regarding fungi, EN 350 [21] defines a system of five durability classes (very durable, durable, moderately durable, slightly durable, and not durable). This system is used to classify heartwood only, while the sapwood is always considered not durable.

Concerning the insects, the same standard [21] establishes two classes for wood boring insects to classify the sapwood (durable and susceptible) and one extra class for cases in which heartwood is also susceptible (susceptible in heartwood). On the other hand, three classes are defined for termite attacks on heartwood (durable, moderately durable, and susceptible), while the sapwood is always considered susceptible [21].

Moreover, EN 350 [21] also establishes a four-class system relating the species to its treatability (easy to treat, moderately easy to treat, difficult to treat, and extremely difficult to treat). Tables 1 and 2 present the classification attributed to two common species in Europe: one softwood, scots pine (*Pinus sylvestris*) and one hardwood, chestnut (*Castanea sativa*).

Table 1: Natural durability and treatability classification of Scots pine [21].

Natural durability		
Fungi		Moderately/slightly durable
Subterranean termites		Susceptible
Wood boring insects	*Anobium punctatum*	Susceptible
	Hylotrupes bajulus	Susceptible
Treatability		
Sapwood		Easy to treat
Heartwood		Difficult/extremely difficult to treat

Table 2: Natural durability and treatability classification of Chestnut [21].

Natural durability		
Fungi		Durable
Subterranean termites		Moderately durable
Wood boring insects	*Anobium punctatum*	Susceptible
	Hylotrupes bajulus	-
Treatability		
Sapwood		Moderately easy to treat
Heartwood		Extremely difficult to treat

The natural durability and treatability classifications established in EN 350 [21] are used to define whether a wood species is suitable to be used or not according to its use class, established in EN 335 [22], and the guidance to correlate the natural durability/treatability to the use classes are provided by EN 460 [23]. EN 335 [22] defines a 5-class system that correlates the exposure condition of wood to the environment during its service life, the frequency at which the wood reaches a high moisture content, and the possibility of occurrence of biological agents. Table 2 presents a summary of the classes of use considered by EN 335 [22].

Table 3: Use classes for solid wood application, adapted from [22].

Use class	**General service situation**	**Moisture Content of the wood**	**Occurrence of biologic agents***			
			Fungi	**Termites**	**Beetles**	**Marine borers**
UC 1	Interior, dry	≤ 20%				
UC 2	Interior, or under cover, not exposed to the weather. Possibility of water condensation.	Occasionally > 20%				
UC 3	Exterior, above ground, exposed to the weather.	frequently wet > 20%				
UC 4	Exterior in ground contact and/or fresh water.	Predominantly / permanently > 20%				
UC 5	Permanently or regularly submerged in salt water	Permanently > 20%				

*Referring to the situation in Portugal; Level of risk: Red - Very high; Orange - High; Yellow - Low; Green - None

For example, EN 460 [23] states that, to be used in use class 4 without prior treatment, the species must have a classification for natural durability against fungi durable or very durable. In the case of Chestnut and Scots pine, when applying the EN 350 [21], EN 335 [22], and EN 460 [23] durability standards, it is possible to conclude that only the first is suitable to use class 4 without previous treatment.

Both normative references consider the relationship between water and wood when defining the guidelines (exposure and absorption/desorption characteristics), considering that, generally, wood with higher permeability is easier to treat but presents lower natural durability, showing the relevance of the moisture content in the process of biological deterioration.

In recent years, efforts have been made by the technical committee CEN/TC 38 'Durability of wood and wood-based products' to review the durability standards in order to provide increasingly reliable documents that meet the current needs of test methods and information about the service life of wooden structures and the influence of key factors, such as exposure to moisture, design and climatic variations [24].

4. CONCLUSIONS

Regarding the various parameters that influence the biological degradation of wood, moisture content is a key factor in controlling the process. Its recognized relevance is reflected in several recent studies that seek to establish correlations with the rate of decay, loss of mechanical properties, and consequent reduction in service life. Therefore, continuous monitoring methods associated with periodic maintenance and physical protection systems to replace preventive treatments with historically used chemical products is considered the path to ensure the integrity of structures, increasing the service life and reducing the costs of rehabilitation.

Although there is an extensive literary background on the biological degradation of wood, more work should be carried out at larger scales, considering its effects on wooden structures and expanding degradation models for different biological agents that are able to encompass the great diversity of wood species, designs, and existing exposure conditions.

Regarding European normative references on the durability of wooden structures, they already take into account the moisture content and absorption properties of the species as a parameter to define classification systems for natural durability, treatability, and risk of deterioration. However, they need constant development and updating to englobe in a versatile way all the variables that must be considered.

Finally, the resurgence of wood as a structural material creates a series of challenges for engineers and architects to develop designs and solutions that take full advantage of its characteristics. Therefore, in order to guarantee the structural, sustainable, and functional performance required nowadays, the full understanding of the biological degradation process and its relation to the moisture content is primordial.

5. BIBLIOGRAPHY

[1] Tegel W, Elburg R, Hakelberg D, Stäuble H, Büntgen U. Early Neolithic water wells reveal the world's oldest wood architecture. *PLoS ONE.* 2012; 7(12):e51374. https://doi.org/10.1371/journal.pone.0051374

[2] Jeffree M. Wood – Building the bioeconomy. Brussels, Belgium: The European Confederation of Woodworking Industries; 2019. https://www.cei-bois.org/publications (accessed: October 2021).

[3] EU climate action & Green Deal. https://ec.europa.eu/clima/policies/eu-climate-action_en (accessed: October 2021).

[4] Cruz H, Jones D, Nunes L. Wood. *In* Gonçalves MC, Margarido F (Eds.), Materials for construction and civil engineering. Science, Processing and Design. Switzerland: Springer; 2015: 557-583 p. https://doi.org/10.1007/978-3-319-08236-3_12.

[5] Verbist M, Nunes L, Jones D, Branco JM. 11 - Service life design of timber structures. In Ghiassi B, Lourenço PB, Civil and Structural Engineering: Long-term Performance and Durability of Masonry Structures. Woodhead Publishing; 2019: 311-336 p. https://doi.org/10.1016/B978-0-08-102110-1.00011-X

[6] Goodell B. Fungi involved in the biodeterioration and bioconversion of lignocellulose substrates. *In* Benz JP, Schipper K (Eds.), Genetics and Biotechnology. The Mycota (A Comprehensive Treatise on Fungi as Experimental Systems for Basic and Applied Research), vol. 2. Springer; 2020. https://doi.org/10.1007/978-3-030-49924-2_15

[7] Govorushko S. Economic and ecological importance of termites: A global review. *Entomological Science*. 2019; vol. 22, pp. 21-35. https://doi.org/10.1111/ens.12328

[8] Brischke C, Alfredsen G. Wood-water relationships and their role for wood susceptibility to fungal decay. *Appl Microbiol Biotechnol*. 2020; 104:3781–3795. https://doi.org/10.1007/s00253-020-10479-1

[9] Palma P, Steiger R. Structural health monitoring of timber structures – Review of available methods and case studies. *Construction and Building Materials*. 2020; 248. https://doi.org/10.1016/j.conbuildmat.2020.118528

[10] Broda M. Natural Compounds for Wood Protection against Fungi – A Review. *Molecules*. 2020; 25. https://doi.org/10.3390/molecules25153538

[11] EN 13183. Moisture content of a piece of sawn timber. Brussels, Belgium: European Committee for Standardization CEN; 2012.

[12] LNEC. Memória M9 - Humidade da madeira. In LNEC, Madeira para Construção; 1997.

[13] Engelund Thybring E, Kymälänen M, Rautkari L. Experimental techniques for characterising water in wood covering the range from dry to fully water-saturated. *Wood Sci Technol*. 2018; 52:297-329. https://doi. org/10.1007/s00226-017-0977-7

[14] Dietsch P, Franke S, Franke B, Gamper A, Winter S. Methods to determine wood moisture content and their applicability in monitoring concepts. *J Civil Struct. Health Monit*. 2015; 5:115-127. https://doi. org/10.1007/s13349-014-0082-7

[15] Forsén H, Tarvainen V. Accuracy and functionality of hand held wood moisture content meters. Finland; VTT, Espoo; 2000.

[16] Brischke C, Rapp AO, Bayerbach R. Measurement system for long-term recording of wood moisture content with internal conductively glued electrodes. *Building and Environment*. 2008; vol. 43:1566–1574 p. https://doi.org/10.1016/j.buildenv.2007.10.002

[17] Schmidt E, Riggio M. Monitoring Moisture Performance of Cross-Laminated Timber Building Elements during Construction. *Buildings*. 2019; vol. 9 no. 6. https://doi.org/10.3390/buildings9060144

[18] Brischke C, Thelandersson S. Modelling the outdoor performance of wood products – A review on existing approaches. *Construction and Building Materials.* 2014; vol. 66:384-397 p. https://doi.org/10.1016/j.conbuildmat.2014.05.087
[19] Gaspari A, Giongo I, Piazza M. A Risk-Based Approach for Quantifying Durability and Life-Expectancy of the Wall-Foundation Construction Detail in Timber Buildings. Proceedings of XV International Conference on Durability of Building Materials and Components. Barcelona, Spain; Oct. 2020 https://doi.org/10.23967%2Fdbmc.2020.004

[20] Viitanen H, Ritschkoff AC, Paajanen L. The durability of different wood products. In European Timber Buildings as an Expression of Technological and Technical Cultures. 2002; 173-186.

[21] EN 350. Durability of Wood and Wood-Based Products. Testing and Classification of the Durability to Biological Agents of Wood and Wood-Based Materials. Brussels, Belgium: European Committee for Standardization CEN; 2016.

[22] EN 335. Durability of Wood and Wood-Based Products. Use Classes: Definitions, Application to Solid Wood and Wood-based Products. Brussels, Belgium: European Committee for Standardization CEN; 2013.

[23] EN 460. Durability of wood and wood-based products. Natural durability of solid wood Guide of the durability requirements for wood to be used in hazard classes. Brussels, Belgium: European Committee for Standardization; 1994.

[24] Kutnik M, Suttie E, Brischke C. Durability, efficacy and performance of bio-based construction materials: Standardisation background and systems of evaluation and authorisation for the European market. *In* Jones D, Brischke C, Performance of Bio-based Building Materials. Woodhead Publishing; 2017: 593-610 p. https://doi.org/10.1016/B978-0-08-100982-6.00010-0