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MICROWAVE TECHNOLOGY AND ITS APPLICATIONS TO WOOD TREATMENT AND MODIFICATION

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ABSTRACT: Humanity has utilized wood, a renewable resource, for a long time. To capitalize on all of the wood's advantages as a building, structural, and furnishing material, the wood industries and academics have continuously sought innovative approaches that lead to better and larger usage of wood. Microwave (MW) treatment is a technology that has gained increased popularity in modifying wood properties. It has been applied to improve the drying quality, increase fluid permeability, and enhance the treatability and impregnability of wood specimens. Therefore, this paper aims to present a summarized state of the art about MW treatment for wood modification and study the application of MW energy to drying wood samples of the Portuguese *Pinus Pinaster*, investigating the changes in the water uptake and compressive strength parallel to the grain of the MW-treated and control specimens. Based on the results, it was identified that there was an average energy consumption of 1233 MJ/m^3 and an average energy application of 3038 MJ/m^3. In addition, the water uptake of MW-treated samples increased by four times, and their compressive strength parallel to the grain was reduced by 19 % compared to the control samples.

KEYWORDS: Microwave treatment, Literature review, *Pinus pinaster*, Water uptake, Compressive strength.

1 INTRODUCTION

Wood is a natural material that has been used for many centuries for different purposes. Nevertheless, certain wood species have low permeability, which causes problems throughout the lumber manufacturing process, such as lengthy drying durations, material losses after drying, expensive drying procedures [1], and even difficulties in impregnating wood elements with preservative agents [2].

Because of this, wood industries and researchers have increasingly sought technologies, procedures, and innovations that address the limitations that wood might have and improve the use of wood in several fields, such as civil construction. Hence, wood modifications, either chemical, impregnation, or thermal, are modern technologies that have been changing the wood industry and research. The goal is to increase the performance of wood or wood-based products, resulting in gains in dimensional stability, improvements in mechanical properties, decay, and weathering resistance [3]–[5].

The use of microwave (MW) energy to dry, treat or modify wood species has been a promising technology with several possibilities of application. MW energy was first created for communication purposes, and then it started to be used for food heating in 1945/1946 [3,4]. It has also been used to heat materials such as wood [2]. MW are electromagnetic energies that interact with the molecules of the materials at different frequencies [6–8]. Because water molecules have a strongly polar structure, they can absorb MW energy and convert it into heat [11], [12]. The water molecule's angular geometry produces a hydrogen and oxygen atom–based dipole at the angle's bisector. When exposed to an electric field, the dipole will alter its orientation. The positive end of the dipole experiences a torque in the positive field direction, whereas the negative pole aligns with the positive field direction. If the field is made to alternate, the molecule will oscillate as it seeks to align with the current field direction [11]. Thus, this movement generates heat.

The use of MW energy in wood elements effectively reduces the drying time, improves its quality, and enhances permeability, contributing to increasing the preservative uptake [5,8–10].

Data from the Portuguese National Forest Inventory shows that maritime pine (*Pinus pinaster*) is the most common softwood in Portugal, representing 22% of the total [15]. Pine trees have rapid development and strong adaptation to varied environmental circumstances, so they are key raw resources that may satisfy some present market needs [16]. Because it has been utilized in construction as a raw material for furniture, poles, and posts, it is one of the most significant wood species in Portugal from an economic standpoint [17], [18]. It is also important to mention that in the case of Portuguese woods, only wild maritime pine appears in the European

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standards with defined classification and testing procedures [19]. Hence, it is vital to comprehend all potential uses of this wood species for the wood sector, given the significance of this pine species in the economics and forestry of Portugal, as well as the rest of the Iberian Peninsula and other European areas, and the significance of forest sustainability [18], [20].

Given the importance of maritime pine for Portuguese construction and economy and the advantages that MW technology has for wood modification, this paper aims 1) to present the most relevant and recent studies regarding MW treatment for wood modification, pointing out the main usages and the scientific research possibilities, i.e., a brief literature review; 2) to analyze the improvement in water uptake (absorption) as an indirect way to analyze the improvement in the capability of being impregnated with preservative agents; and 3) to investigate the variations in the ultimate stress in compression parallel to the grain of wood samples with and without MW treatment of the Portuguese maritime pine.

2 MICROWAVE TREATMENT AND ITS MAIN APPLICATIONS – REVIEW

MW modification of wood is a new technology [5,11,12] with major applications for reducing wood drying time and improving fluid permeability [2]. When MW is applied, some parameters need to be adjusted to have different levels of MW wood modification: wood initial moisture content (IMC), MW power, frequency, energy supplied to the wood (intensity), and exposure time [5,8].

Wood industries have great concerns about the refractory species [21], which have low permeability and might show problems either during drying, impregnation, or retention of protective agents [10].

Conventional wood drying processes are time-consuming. Drying hardwood species might take long periods, and undesirable drying effects may emerge from it [10]. When MW wood drying is appropriately used, it can reduce the drying time and defects [2] and overcome the issue of hardwoods collapsing during drying [10].

In contrast to conventional wood drying, where heat is conducted from the outer layers towards the inner of the specimen through convection, conduction, and radiation, electromagnetic waves penetrate the entire volume of the sample in MW drying (treatment), promoting volumetric heat absorption by the wet wood [12], [23]. According to Sahin and Ay [23], energy is conveyed in the traditional drying heat process due to thermal gradients in the material; however, in microwave heating, electromagnetic energy is transformed into thermal energy rather than heat transmission. It produces rapid heating over the thickness of the material while also decreasing thermal gradients. Volumetric heating can also help to reduce drying times and conserve energy.

Wood is a biomaterial, so water plays an important role in it [21]. When MW energy hits the wood, the absorbed energy generates random vibrations of water molecules [13,14]. This motion raises the interior temperature of the wood, creating steam pressure that can quickly reach 600 kPa [10], [25], [26]. This increasing steam pressure damages the wood cell tissue to varied degrees [27]. Micro-structures that are prone to rupture include brittle ray cells, pit membranes in cell walls, and tyloses in arteries [28]. Variations in porosity and pore diameter distribution may result from changes in microstructure, opening up new channels for the easier passage of liquid. As a result, they affect crucial end-product qualities, such as permeability [28], [29] and absorption and retention of preservative agents [2].

The retention of acid copper chromate by MW-treated samples of *Eucalyptus tereticornis* increased by more than 375% after high-intensity MW treatment, from 2.03 kg/m^3 to 9.72 kg/m^3 [30]. Compared to wood samples without MW treatment, the absorption of Tanalith E in Spanish *Eucalyptus globulus* L. samples treated with MW increased by 148% [13].

After the MW treatment, Samani et al. [31] discovered a substantial improvement in the preservative retention and penetration of MW-treated wood specimens of Melia composita compared to the samples with no MW treatment. Compared to the control group, the retention capacity of *Pinus roxburghii* Sarg samples treated with MW was reported to be two times larger [32]. In addition, after submitting wood samples of Picea orientalis to an MW treatment with applied energy of 2158 MJ/m^3, Kol and Çayır [33] impregnated them with Tanalith E 8000. Their results showed that the retention rate increased by 61% compared to wood samples with MW treatment [33].

According to Wang et al. [34], MW treatment altered the chemical structures of cellulose, hemicellulose, and lignin, the three main constituents of wood. In contrast, lignin and cellulose were relatively stable. They only modified under limited circumstances, and hemicellulose sustained significant harm [34].

Both the physical and mechanical properties of wood are impacted by the microstructural changes that MW treatment causes to the wood cells. The damage in wood microstructure (and even macrostructure) increases when more MW energy is applied to the wood. Studies carried out by Weng et al. [27], [35], [36] using scanning electron microscopy (SEM) demonstrated that increased MW energy led to an increase in damage to wood microstructure. Numerous cavities were formed in the wood due to the high MW energies used, changing its porosity, permeability, strength, and flexibility [10]. The density of MW-treated samples tended to be lower than that of untreated samples, according to experimental research [10], [37], [38].

Several investigations have demonstrated that the values of modulus of rupture (MOR) and other strength parameters of MW-treated samples may decrease to varying degrees depending on the MW power and exposure period [10], [13], [21], [33], [38], [39]. According to Torgovnikov and Vinden [10], the degree of alteration that may be assigned to structural changes in wood following MW treatment – low, moderate, and high – depends on the MW treatment circumstances. The authors stated that there was no effect on the mechanical characteristics of wood and an increase in permeability of up to 1.5 times with low degrees of alteration. The moderate degree of alteration decreases the mechanical qualities of wood while increasing permeability 1,000 times. Finally, a high degree of modification greatly increases permeability but greatly decreases mechanical properties [10].

Weng et al. [14] employed two MW powers, 15 and 20 kW, to treat wood samples of *Cunninghamia lanceolate* (Lamb.) Hook. The authors demonstrated that the damage to the wood microstructure was more severe under high MW treatment power (20 kW). For 20 kW, the produced macro-cracks were between 100 and 130 μm wide, while for 15 kW, they were between 1 and 25 μm wide. For 15 kW and 20 kW, the diameter of margo capillary holes in pit membranes increased by 23% and 55%, respectively. In addition, the results from the literature have demonstrated that the influence of the applied energy directly impacted the density and the mechanical properties of different wood species.

According to Torgovnikov and Vinden [10], samples with heartwood lost more strength than samples with only sapwood under the same MW applied energy, for example, to produce a modest degree of modification. This resulted in a slight change in the MOR. Mascarenhas et al. [40] also demonstrated a significant improvement in water uptake of small clear wood specimens of Portuguese maritime pine containing only heartwood compared to the samples containing only sapwood, demonstrating the necessity of providing the sapwood sample with more MW energy. This improvement in water uptake was demonstrated by drying wood samples with only sapwood and heartwood under the same MW parameters. In light of these results, it can be concluded that the density of the wood component was, in fact, a major parameter (that affects) the fluctuations in the MOR values following MW treatment.

According to Wang et al. [34], utilizing MW intensities (applied energy) ranging from 72 MJ/m^3 to 288 MJ/m^3, neither the cell architectures nor the cell wall morphology of any of the samples with an IMC of 40% changed substantially. On the other hand, the worst alterations to the cell wall structure were caused by MW treatments in wood samples with an IMC of 20% and applied energy of 288 MJ/m^3. As a result, the decline in the mechanical properties values of the wood samples treated with MW was closely related to the harm caused to the cell morphology.

He et al. [29] indicated that under the adopted MW treatment parameters, no significant influence was detected in the MOR values of wood samples with IMC over the fiber saturation point (FSP) (greater than 40%). Then, for these circumstances, the drop in mechanical characteristics during static bending tended to be less the greater the initial MC.

According to the results reported in the literature, the effects of MW treatment on strength and stiffness rely not only on the MW treatment parameters but also on the type of wood and IMC. Furthermore, it is challenging to impregnate wood with resins and preservatives. Wood components may be more easily impregnated with substances to boost biological and fire resistance because of their increased permeability due to MW treatment. They can even be used to create new wood-based products that are impregnated with polymers that have improved qualities [2], [10], [25].

3 MATERIALS AND METHODS

3.1 SAMPLE PREPARATION

Small clear heartwood specimens of the Portuguese maritime pine with 20 mm × 20 mm × 200 mm (radial × tangential × longitudinal) (Figure 1) from the Centre region of Portugal were obtained from commercial boards. The idea of using them is because they allow a safer comparison of results between different wood species [41], [42]. Small clear specimens also have better workability, are simple to obtain, economically attractive, rapid to condition, and straightforward in tests, for example, mechanical ones [43], [44].

In total, 24 specimens were used. They were divided into two groups, control (no MW-treated) and MW-treated, which were submitted to the MW treatment (MW drying). Table 1 shows the number of samples per group, their average initial moisture content (IMC), and standard deviation values.

Figure 1: *Small clear specimen of Maritime Pine*

Table 1: *Sample groups, their quantity, and IMC*

Group	Designation	Quantity of specimens	Average IMC (%)	Standard deviation (%)
HP_MW	Heartwood Pine – MW-treated	12	83.44	16.33
HP_Control	Heartwood Pine – Control	12	12.55	5.43

The wood samples submitted to the MW treatment were placed in a container of distilled water to preserve their "green" conditions so they would not lose water until the drying process began.

3.2 MICROWAVE TREATMENT

The MW treatment was carried out in a conventional MW device measuring 200 mm × 300 mm × 300 mm, at a frequency of 2.45 GHz, with a turntable that allowed a homogeneous distribution of the MW waves.

The wood samples were dried using full MW power of 800 W until they achieved an average final moisture content of 12 %. The MW treatment schedule is shown in Figure 2.

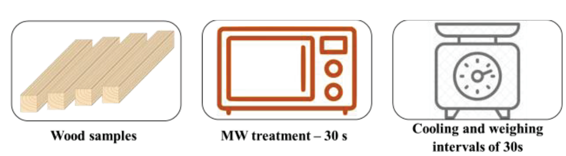

Figure 2: *MW treatment schedule*

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As seen in Figure 3, four wood specimens were placed inside the MW oven during each MW drying cycle. The wood samples were exposed to continuous MW energy for 30 s, removed during a colling interval of 30 s to measure the samples' weight (and then to have the moisture content profile along the MW treatment process), and then placed again inside the MW oven.
The cooling intervals were necessary for measuring the weight of the specimens as well as for preventing overheating, which might seriously damage the wood. A similar approach was made by [11], [33], [45]. Oloyede and Groombridge [11] noticed that each succeeding MW exposure should have a larger penetration depth and that by cycling the drying process, the wood might be efficiently dried to any moisture content.

Figure 3: *Pine samples during the cooling interval*

The energy required to heat moist wood and vaporize the water in the wood, Q_w, was calculated according to equation (1) [46].

$$Q_w = \Delta T \cdot (c_1 \cdot m_1 + c_2 \cdot m_2) + \Delta m \cdot r \quad (1)$$

Where: Q_w is the energy required to heat moist wood and to vaporize the water in the wood, in kJ (kWs); ΔT is the temperature difference, in ºC; c_1 is the heat capacity of water, 4.18 kJ/kgºC; m_1 is the mass of water in the specimen, in kg; c_2 is the heat capacity of dry wood, 1.36 kJ/kgºC; m_1 is the mass of dry wood in the specimen, in kg; Δm is the mass of vaporized water, in kg; r is the heat of vaporization of water at 100ºC, 2250 kJ/kg.
The average effective power density consumed to dry the wood specimens is given by Equation (2) [46].

$$P_\delta = \frac{Q_w}{V.t} \quad (2)$$

Where: P_δ is the specific power density consumed to dry the wood specimens, in kW/m^3; V is the volume of wood specimen, in m^3; t is the drying time, in s.
The specific energy consumption during the process is given by Equation (3) [46].

$$E_{in} = \frac{P_\delta \cdot t}{1000} \quad (3)$$

Where:E_{in} is the specific energy consumption during the process, in MJ/m^3.

The specific energy supplied during the process is given by Equation (4) [33].

$$E_{out} = \frac{P \cdot t}{V \cdot 10^6} \quad (4)$$

Where:E_{out} is the specific energy supplied during the process, in MJ/m^3; P is the MW power supplied.
Finally, the overall MW efficiency, η, was calculated according to equation (5).

$$\eta = \frac{E_{in}}{E_{out}} \quad (5)$$

Once the MW treatment was completed, the mass percent loss (MPL) was calculated using equation (6):

$$MPL\ (\%) = \frac{M_f - M_i}{M_{od}} \times 100 \quad (6)$$

where MPL is the mass percentage loss, in %; M_f is the mass of the sample after the MW treatment, in grams; M_i is the mass of the samples before MW treatment, in grams; M_{od} is the oven-dry mass, in grams.

3.3 WATER UPTAKE

Both wood groups were impregnated with distilled water under constant pressure for 30 min. The water uptake (W) was measured using equation (7):

$$W\ (\%) = \frac{M_a - M_b}{M_{od}} \times 100 \quad (7)$$

where W is the water uptake, in %; M_a is the mass of the sample after the water impregnation at the instant in which it was measured, in g; M_b is the mass of the MW-treated samples before the impregnation, in g.

3.4 COMPRESSION STRENGTH PARALLEL TO THE GRAIN

The average ultimate stress in compression parallel to the grain at 12 % moisture content, $f_{c0,12\%}$, was evaluated according to ISO 13061-17 [47]. Wood specimens measuring 20 mm x 20 mm x 60 mm were used in this mechanical test. Before the compression tests, the wood samples were conditioned at a temperature of 20 °C ± 2 °C and 65 % ± 5 % of relative humidity for 14 days to achieve their equilibrium moisture content.

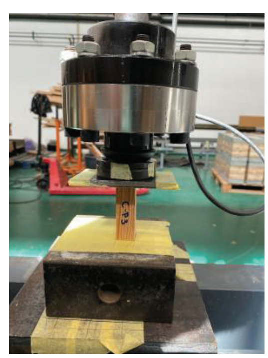

Figure 4: *Compression parallel to the grain test according to ISO 13061-17* [47]

3.5 STATISTICAL ANALYSIS

Pearson's correlation coefficient (r) measures the degree of linear correlation between two quantitative variables. This approach typically uses datasets with a normal distribution and an interval or continuous scale [48]. It can range from -1 to +1, presenting a low, moderate, or strong correlation, where a 0 value means that there is no correlation. It is calculated according to Equation 8:

$$r(X_i, Y_i) = \frac{cov(X_i, Y_i)}{\sqrt{var(X_i) \times var(Y_i)}} \quad (8)$$

Where: X_i and Y_i are the datasets of the MW-treated woods, $cov(X_i, Y_i)$ is the covariance, $var(\cdot)$ is the variance.

Simple linear regression models, which have one dependent variable (Y) and one independent variable (X), were used with Pearson's correlation coefficient to analyze the correlation between the $f_{c0,12\%}$ and the water uptake of the MW-treated wood samples. The general equation for a linear regression model is:

$$Y = b_0 + b_1 X \quad (9)$$

Where: Y is the dependent variable as output, X is the independent variable as input, b_1 is the regression coefficient, b_0 is the constant.

The analysis of variance (ANOVA), at a 5 % significance level, using Minitab Software (Version 18) [50], was applied to study the effectiveness of the MW treatment in improving the water uptake and the changes in the compressive strength of maritime pine wood samples. According to the ANOVA formulation, if p-values are smaller than the significance level (p-value ≤0,05), the samples (control group and MW-treated) can be considered different.

4 RESULTS AND DISCUSSION

4.1 MW DRYING

Once a total of 12 specimens were dried, and each treatment scheme was done with four specimens dried together, three rounds of drying were performed. Based on this, the average values of the MW drying (treatment) of the pine heartwood samples are shown in Table 2. The total time the wood samples were exposed to MW energy was, on average, 21 min, with a maximum of 27 min. The average effective power density, P_δ, to dry the wood specimens was 1005 kW/m^3, the average energy consumed, E_{in}, was 1233 MJ/m^3, and the average energy applied, E_{out}, was 3038 MJ/m^3, with an overall MW efficiency of 0.40 (average) and a maximum value of 0.46. According to [12], [46], the overall MW efficiency for MW ovens with industrial applications is approximately 0.50. Therefore, our results are in accordance with this value.

Table 2: *MW drying information*

Group	Average total MW exposure time (s)	P_δ (kW/m^3)	E_{in} (MJ/m^3)	E_{out} (MJ/m^3)	η
HP_MW	1260 (383)	1005 (131)	1233 (239)	3038 (958)	0.40 (0.05)

The values in brackets are the respective standard deviation.

In addition to this, Table 3 presents the average MPL and the amount of energy per MPL. The MPL average value was 67.17 %, ranging from 51.60 to 82.74 %. Based on these results, the consumed energy used to obtain 1 % of MPL was 17.78 MJ/m^3, i.e., it was consumed, on average, 17.78 MJ/m^3 to evaporate 1 % of the water from the wood samples. In addition, it was supplied 44.37 MJ/m^3, to have 1 % of MPL, which is in accordance with the previous results, such as the ones found by [33], [51], whose values ranged from 43.60 to 50.30 MJ/m^3.

Table 3: *Information about MPL after MW treatment*

Group	MPL (%)	E_{in}/MPL (MJ/m^3/%)	E_{out}/MPL (MJ/m^3/%)
HP_MW	67.17 (17.07)	17.78 (0.98)	44.37 (3.82)

The values in brackets are the respective standard deviation.

The average MW drying rate was 3.19 %/min, and the maximum was 6.31 %/min. Figure 5 shows the MW drying rates over the drying time. Drying small clear samples of another pine species, *Pinus banksiana*, applying an MW power of 800 W, Ouertani *et al*. [21] identified a maximum drying rate slightly higher than 6 %/min.

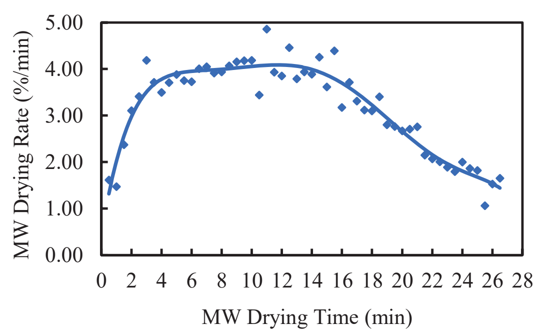

Figure 5: *MW drying rate*

Three stages can be seen in Figure 5. First, the drying rate increased, which may be interpreted as the time when a portion of the energy input was used to raise the temperature of both the water and the wood material from room temperature to around 100 ºC. After then, the drying rate remains relatively steady for the whole drying process. As the amount of free water in the wood approached zero, the drying rate decreased in the last stage.

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4.2 WATER UPTAKE

The water absorption of the MW-treated and control wood specimens was measured through their water uptake, and the results can be seen in Figure 6. The average W of HP_MW was 42.57 % (stand. dev. of 16.69 %), and the average W of HP_Control was 10.32 % (stand. dev. of 3.63 %). Thus, the MW treatment significantly impacted the water uptake of MW-treated samples at a confidence level of 95%, i.e., it was almost six times higher.

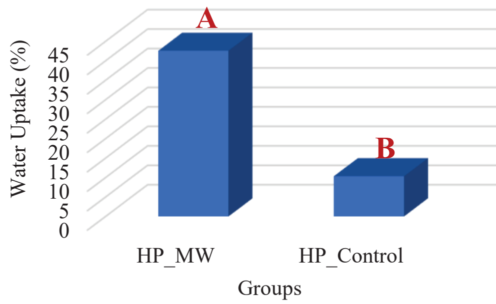


Figure 6: *Water uptake (W) of the wood samples (Values followed by the same letter do not differ significantly at α=0.05)*

According to EN 350 [52], the treatability, which is "the ease with which a wood can be penetrated by a liquid (for example, a wood preservative)" of maritime pine's heartwood, is considered extremely difficult to treat. This fact can be seen in the water uptake value of the wood control samples. Since the water uptake of the MW-treated samples increased, it might indicate that the permeability of the MW-treated sample enhanced, which may be beneficial for easier impregnating those heartwood pine samples with preservative chemicals.

4.3 COMPRESSION STRENGTH PARALLEL TO THE GRAIN

Compression is an important mechanical property in designing different elements, such as poles, trusses, and columns. The newest version of the Brazilian Timber Structures Code, ABNT NBR 7190-1 [53], uses compressive strength parallel to the grain to classify the batch strength.

The ultimate stress in compression parallel to the grain at 12 % moisture content, $f_{c0,12\%}$, of both wood groups is shown in Figure 7. The average $f_{c0,12\%}$ values for MW-treated and control groups were 61.94 MPa (minimum of 48.51 MPa, maximum of 78.41 MPa, and stand. dev. of 8.70 MPa) and 49.93 MPa (minimum of 36.82 MPa, maximum of 59.94 MPa, and stand. dev. of 7.68 MPa).

Studying the mechanical behavior of small clear samples of maritime pine, Santos [54] found that the average compressive strength of the specimens was 59 MPa.

Besides the compressive strength of studied MW-treated and control specimens being statistically different (at a confidence level of 95 %), the MW treatment of 3038 MJ/m^3 applied energy caused a decrease of approximately 19 % in the compressive strength of the specimens. Using an MW power of 925 W and applied energy of 2158 MJ/m^3, Kol and Çayır [33] identified a reduction of 4 % in $f_{c0,12\%}$ of MW-treated small clear sapwood samples of *Picea orientalis* (L). Link.

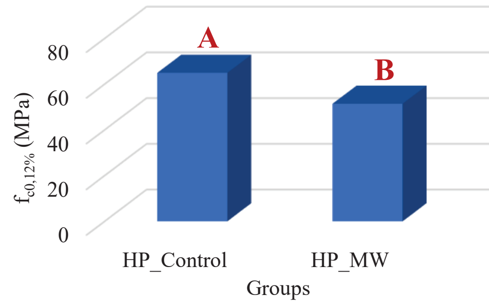


Figure 7: *Results of compression strength parallel to the grain, $f_{c0,12\%}$ (Values followed by the same letter do not differ significantly at α=0.05)*

Load-displacement curves in compression parallel to the grain of control and MW-treated samples are shown in Figure 8(a) and (b), respectively. Overall, both curves demonstrated an initial elastic domain almost up to the maximum applied force and, after that, a plastic behavior. As previously presented, the maximum average compressive stress of the MW-treated specimens is statistically lower than that of the control group specimens, which is also evident when analyzing Figure 8. The maximum average force of control samples was 26.2 kN with an average actuator displacement of 2.21 mm. On the other hand, the maximum average force of MW-treated samples was 21.1 kN with an average displacement of 1.65 mm.

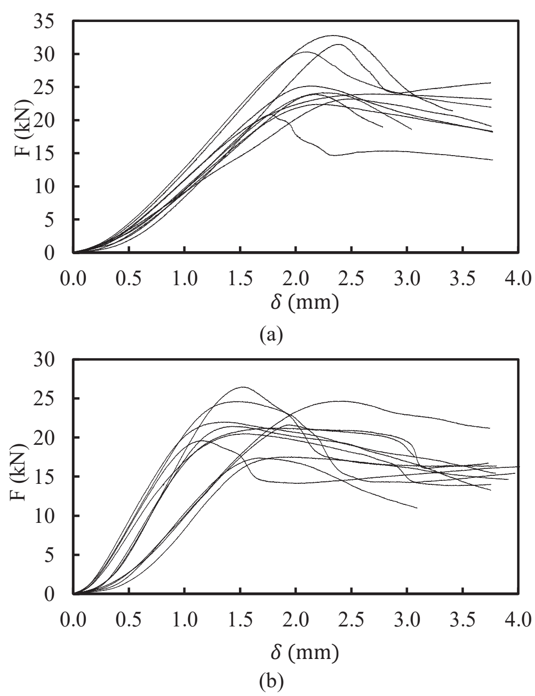
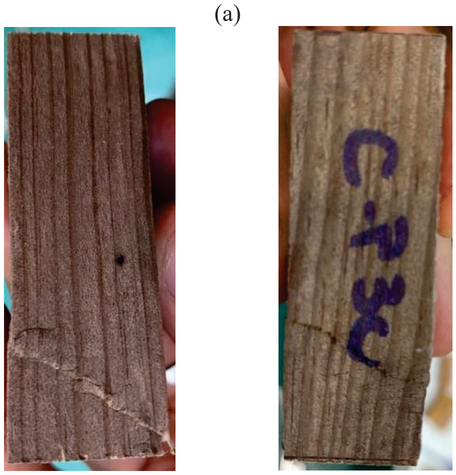


Figure 8: *Load-displacement curves of compression parallel to the grain of (a) control and (b) MW-treated groups (F=Force)*

Figure 7 shows four wood samples of maritime pine, (a) two with no MW treatment and (b) two MW-tread. The most common type of failure in control and MW-treated samples was crushing-shearing, which are normal types of failure according to ASTM D143 [55].

(a)



(b)

Figure 9: *Compression failure mode of (a) control and (b) MW-treated samples*

It is important to explain that the darker color of the MW-treated sample is not because of the MW treatment. As previously explained, the specimens were kept in water to preserve their "green" condition. Therefore, this period that they were immersed in water contributed to the change in their color.

According to Benabou [56], the compressive properties of wood play a crucial role in this behavior. Wood, in particular, exhibits a typical failure pattern known as kink banding when compression parallel to the grain. It is a shear-type failure that occurs in many aligned-fiber composites and wood materials. Benabou [56] also stated that under the kink banding mechanism, three main stages could be recognized (Figures 8 and 10). To begin, incipient kinking occurs in limited areas, beginning with ray cells of wood dispersed throughout the material and causing the stress-strain curve to become non-linear. Fibre shearing and buckling is the softest kind of deformation at this stage. The peak stress occurs shortly after the commencement of nonlinearity and indicates the conclusion of incipient kinking. After that, the transient kinking occurs when the stress decreases from its peak to a steady condition. During this phase, the tiny zones of incipient kinking get bigger and unite to produce a single dominant band with a specific direction across the specimen. The fibers within the band are compressed and rotated at the same time. Fiber rotation increases until the final lock-up position is reached. Due to volumetric preservation considerations, no more deformation inside the band is feasible at this lock-up angle. Third, steady-state kinking happens after fiber lock-up and is caused by continually applied tension, also known as steady-state stress. The band broadens laterally into the surrounding material throughout this period [56].

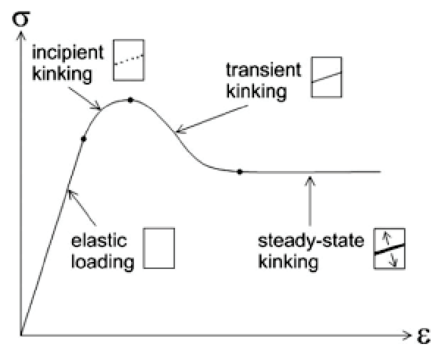


Figure 10: *Diagrammatic representation of the stress-strain crushing behavior of a wood specimen at various kinking stages (From Benabou* [56])

Figure 11 shows Pearson's correlation coefficient r and the p-values. First, the correlation between the ultimate stress in compression parallel to the grain at 12 % moisture content and the water absorption of the MW-treated specimens can be considered moderate to high and significant (p-value<0.05). It is a negative correlation, 0.639, which indicates that the higher the water uptake, the smaller the values of $f_{c0,12\%}$ were. This is easily understandable since a greater water retention capacity may indicate that more damage has occurred in the microstructure of the wood specimens, so this damage negatively affects the mechanical properties.

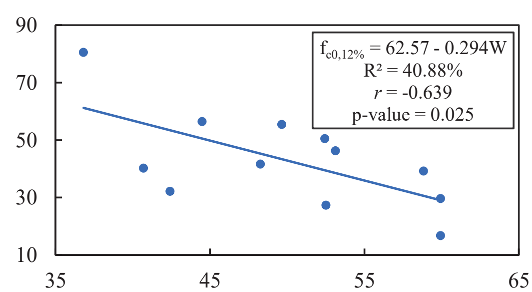


Figure 11: *Correlation analysis*

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5 CONCLUSIONS

Microwave treatment or drying of wood is a modern technique with primary applications in wood drying and increasing the fluid permeability and the impregnation with preservative chemicals. When MW is used, the following main variables must be adjusted to achieve various degrees of MW wood modification and assure its efficiency: wood initial moisture content, MW power, frequency, applied energy (intensity), and exposure time.

Microwave treatments can expand the radius of pit membrane pores and even generate microscopic cracks inside the wood by altering the wood's microstructure (such as the pit and ray parenchyma cells). These effects may lead to increased permeability of wood, which is desirable for many wood species primarily to improve impregnability and retention of preservative chemicals and even to make novel wood-based composites.

Regarding the analysis impacts of the MW treatment on the samples of Portuguese maritime pine containing only heartwood, the following conclusions were drawn:

- With an average IMC of 83 %, there was an average energy consumption of 1233 MJ/m^3 and an average energy application of 3038 MJ/m^3. This gave an overall MW efficiency of 0.40 on average, with a maximum value of 0.46.
- The amount of consumed energy to dry 1 % water was around 18 %, and the amount of applied energy to dry 1 % water was approximately 44 %.
- The average MW drying rate was 3.19 %/min, and three stages were identified: a rapid increase of the drying rate after a constant period and then a decrease of the drying rate.
- An increase of about four times in the water uptake capability of the MW-treated samples compared to the control group was measured.
- A decrease of 19 % in the ultimate stress in compression parallel to the grain of the MW-treated specimens compared to the control group was identified.

Finally, based on the results of this study, MW treatment (drying) of Portuguese maritime pine presents interesting possibilities in increasing the absorption of preservative chemicals without causing significant reductions in the compressive strength parallel to the grain. Hence, fine adjustments in the MW treatment conditions might be made in order to maintain the improvement in the capability of absorbing fluids without causing severe reductions in the mechanical properties, which can be more extensively studied.

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