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EFFECT OF MICROWAVE TREATMENT ON DRYING AND WATER IMPREGNABILITY OF *Pinus pinaster* AND *Eucalyptus globulus*

Fernando Júnior Resende Mascarenhas[1,2,♠]

https://orcid.org/0000-0001-5133-8456

Alfredo Manuel Pereira Geraldes Dias[1,2]

https://orcid.org/0000-0002-9752-1907

André Luis Christoforo[3]

https://orcid.org/0000-0002-4066-080X

Rogério Manuel dos Santos Simões[4]

https://orcid.org/0000-0001-8143-1555

André Eduardo Palos Cunha[4]

https://orcid.org/0000-0003-3903-4075

ABSTRACT

Wood is a material that has been used by humankind for a long time. However, wood researchers and industry have always been concerned about the issues during wood drying and the permeability problems of certain species. In this sense, microwave technology has been applied for wood drying and improving permeability. This paper investigates the microwave drying of two Portuguese wood species, *Pinus pinaster* sap and heartwood, and *Eucalyptus globulus* heartwood using small clear specimens. The samples were grouped into six during each microwave treatment run according to their similarity of initial moisture content. Once the drying was completed, control and microwave-treated samples were impregnated with desalinated water to analyze their improvement in water absorption, and the compression strength parallel to the grain was analyzed. The results showed that each wood species behaves differently under microwave drying and initial moisture content. The impregnation results demonstrated that pine and *Eucalyptus* microwave-treated heartwood samples improved their capability to absorb water. Finally, only the microwave-treated specimens of *Eucalyptus* heartwood presented a decrease in the values of compression strength parallel to the grain compared to the control group. Therefore, MW treatment presents possibilities for further applications for the wood industry with supporting results.

Keywords: Compression strength, microwave treatment, *Eucalyptus*, Pinus, small clear specimens, water uptake.

[1]University of Coimbra, ISISE, Department of Civil Engineering. Coimbra, Portugal.
[2]Innovation and Competence Forest Centre -SerQ. Sertã, Portugal.
[3]Federal University of São Carlos.Department of Civil Engineering. São Carlos, Brazil.
[4]Universidade da Beira Interior. Department of Chemistry. Unit of Fiber Materials and Environmental Technologies (FibEnTech-UBI). Covilhã, Portugal.
♠Corresponding author: fer.jr.resende@hotmail.com
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INTRODUCTION

Engineering applications utilizing wood and wood-based materials have received significant interest in recent years as part of a sustainability policy, mainly owing to their environmental benefits (Majano-Majano *et al*. 2020). Wood is a natural and sustainable material that has been widely used in civil construction and engineering due to its different possibilities of application (Jirouš-Rajković and Miklečić 2021).

Wood is originated from living trees, so water is an important component. Most wood applications require removing a significant portion of the water content from saturated wood, i.e., drying it, to avoid further dimensional variations under different air humidity circumstances, enhance mechanical properties, safeguard the wood elements against biological attacks, and finish or glue wood elements (Leggate *et al.* 2021, Penvern *et al.* 2020).

Based on that, drying is an important and inevitable part of manufacturing wood elements and their further usage (Ndukwu *et al.* 2021, Yin and Liu 2021). Drying under inappropriate conditions and schedules may cause drying defects such as cracks, distortions, and warp, affecting the final use of the wood element and generating more material losses due to, for example, the bigger need to plan the wood pieces (Ross 2010).

Some wood species might have low permeability, impacting their drying and timber processing (Torgovnikov and Vinden 2009), including gluing, finishing, and preservation. For instance, the conventional drying process requires large amounts of energy and takes a long time, and the wood specimens may present checks and cracks due to the drying issues (Aksenov and Malyukov 2020, Balboni *et al.* 2018, Torgovnikov and Vinden 2009). *Eucalyptus*, as a hardwood species, can present challenges during drying. Drying with a microwave (MW) oven might be an option for drying the wood right after sawing, with fewer cracks and material losses (Harris *et al.* 2008, Torgovnikov and Vinden 2010).

Several processes have been used to dry the wood: a kiln, air, vacuum drying (Chuchala *et al.* 2020), and radio frequency (Oloyede and Groombridge 2000). Most of them are time-consuming, capital, and energy-intensive (Haque 2007). Thus, the wood sector is particularly interested in developing new and more energy-efficient drying technologies, enhancing drying rate and quality, and decreasing the environmental impact of traditional drying systems (Herrera-Díaz *et al.* 2018).

Microwave treatment is a modern technology that has been used to dry wood, increasing the drying rate and reducing the drying issues when compared to conventional drying methods (Kol and Çayır 2021, Mascarenhas *et al.* 2021, Poonia *et al.* 2021). When MW energy is in contact with the water present in the wood, the water molecules turn orientated to the electromagnetic field of the MW, causing them to vibrate (Oloyede and Groombridge 2000). This movement of water molecules generates heating, creating steam pressure inside the wood (Oloyede and Groombridge 2000, Torgovnikov and Vinden 2009). Due to the generated vapor pressure differential from wood inside to outside, some wood's cellular structures can be damaged, such as ray parenchyma cells and pit membranes (Weng *et al.* 2020, Xiao *et al.* 2018). This phenomenon ends up creating new paths through which water can pass. Hence, due to improved porosity and permeability in wood, there is an increase in drying quality and permeability (Mascarenhas *et al.* 2021). Besides permeability, several other parameters influence the MW drying of wood, including the thickness of and initial moisture content (M) of the specimens, and the MW treatment of wood has different parameters and behavior depending on the species (Mascarenhas *et al.* 2021).

Several research papers about the MW modification of wood specimens have been developed using small clear specimens and small and commercial microwave ovens, such as the one carried out by Hansson and Antti (2003) that studied Norway spruce (*Picea abies*), Hermoso and Vega (2016) that studied *Eucalyptus globulus* from the Northwest of Spain, Kumar *et al*. (2016) and Poonia and Tripathi (2018) that studied *Pinus roxburghii* Sarg., Ouertani *et al.* (2018) that studied Jack pine (*Pinus banksiana*) wood, Samani *et al.* (2019) that studied *Melia composita*, Ganguly *et al.* (2021) that studied Norway spruce and Kol and Çayır (2021) and Kol and Çayır (2022) that studied Oriental spruce (*Picea orientalis* (L.) Link.).

As verified in the literature, the use of small clear specimens and conventional microwave ovens has shown to be a relevant, practical, and more economical way to study and compare the behavior of different wood species when submitted to MW treatment.

According to data from the 6th Portuguese National Forest Inventory (ICNF 2019), *Eucalyptus* spp. and *Pinus pinaster* represent 26 % and 22 % of the species in Portuguese forests, respectively, and *Eucalyptus* is the wood species that occupies the largest forest area in Portugal. The sawn, pulp, and paper industries, which use primarily domestically produced raw materials (mainly from pine and *Eucalyptus*), are now significant for employment and the economy in Portugal (Rego *et al.* 2013).

Maritime pine (*Pinus pinaster*) forest culture is the basis for the growth of various types of industries, including the manufacture of wood panels and biomass pellets, and the plantation of *Eucalyptus* was responsible for the transformation of Portuguese forest organization (Nunes *et al.* 2019). Maritime pine is the most common softwood in Portugal, and because of that, it is one of the most used species in Portugal. It has been used for structural purposes, housing furniture, outdoor structures such as fences and furniture, floors and coatings (Morgado *et al*. 2013, Morgado *et al*. 2017). Eucalypt wood is mainly used to produce paper, energy, and solid wood elements (Esteves *et al*. 2007, Longue Júnior and Colodette 2013). Therefore, both wood species in Portuguese forests play an important role in Portuguese construction, engineering, and furniture segmentation.

Mascarenhas *et al.* (2021) showed that most of the developed works had investigated the use of MW technology for wood drying and posterior increase in liquids and preservative agents absorption. The MW treatment of some wood species has already been extensively studied. However, according to Mascarenhas *et al.* (2021), a minor part of the studies, lower than 5%, investigated eucalypts, *Eucalyptus globulus*, and none of them was carried out using Portuguese Maritime pine, *Pinus pinaster*. It is not yet well established how the heartwood and sapwood of Portuguese maritime pine behave when subjected to MW treatment and the gains in terms of increased water uptake of *Eucalyptus*.

This work presents a study regarding the microwave drying of two Portuguese species, Maritime pine (*Pinus pinaster*) and eucalypts (*Eucalyptus globulus*). Thus, the objective is to evaluate the MW drying of heartwood specimens of *Eucalyptus globulus* and sap and heartwood specimens of *Pinus pinaster* and analyze the differences between these two wood species. Moreover, it is aimed to analyze the improvement in water impregnability (absorption) of the MW-treated wood samples and the variations in the compression strength parallel to the grain.

MATERIALS AND METHODS

Heartwood samples of *Eucalyptus globulus* Labill and sap and heartwood samples of *Pinus pinaster* of Portuguese forests were obtained from commercial boards. A total of 132 small clear wood specimens with the dimensions of 10 mm x 10 mm x 200 mm (radial x tangential x longitudinal) were cut and prepared at the SerQ -Innovation and Competence Forest Centre. The idea of using small clear wood specimens is because they allow the results can be more safely compared to other wood species (Melo *et al.* 2015, Lorenzo and Muñoz 2018), allowing better workability, they are simple to obtain, economically attractive, rapid to condition, and straightforward in tests, for example, mechanical ones (Cunha *et al*. 2021, Krajnc *et al*. 2019).

Wood specimens were identified with letters and numbers to indicate the species and whether they were sap or heartwood, as shown in Figure 1. The use of small clear specimens of wood enables that the effect of defects such as knots and cracks to be eliminated, allowing a safer comparison of wood characteristics (Melo *et al.* 2015). Half of the wood specimens were MW-treated, and half were from the control group kiln-dried (with no MW treatment).

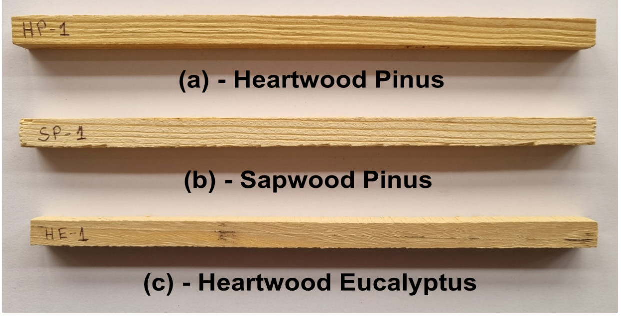

Figure 1: Wood samples, (a) Heartwood *Pinus*, (b) Sapwood *Pinus*, (c) Heartwood *Eucalyptus*.

Likewise done by Kol and Çayır (2021), some specimens were randomly selected to determine their oven-dry weight, w_{od}. The initial moisture content (MC) of the samples groups is presented in Table 1. Heartwood *Pinus* (HP) and Sapwood *Pinus* (SP) groups stand for heartwood and sapwood of Maritime Pine, and Heartwood *Eucalyptus* (HE) for heartwood of *Eucalyptus*. The control groups (with no MW treatment) were Control-HP, Control-SP, and Control-HE, for heartwood *Pinus*, sapwood *Pinus*, and heartwood *Eucalyptus*, respectively.

Table 1: Sample groups, their quantity, and initial MC.

Group	Number of Samples	Average initial MC (%)	Standard Deviation (%)	IC (95%)* (%)
HP-I	6	76,17	5,23	(70,68; 81,65)
HP-II	6	81,82	3,65	(77,99; 85,65)
HP-III	6	91,06	7,72	(82,96; 99,16)
HP-IV	6	93,99	9,42	(84,11; 103,88)
SP-I	6	115,53	2,18	(113,24; 117,82)
SP-II	6	126,12	1,77	(124,26; 127,98)
SP-III	6	128,53	0,52	(127,99; 129,07)
SP-IV	6	132,68	1,85	(130,74; 134,63)
HE-I	6	56,95	2,47	(54,35; 59,54)
HE-II	6	63,40	1,80	(61,51; 65,28)
HE-III	6	72,43	6,03	(66,10; 78,75)
Control-HP	24	9,00	7,79	(6,03; 11,96)
Control-SP	24	12,57	5,81	(10,36; 14,79)
Control-HE	18	9,46	4,28	(7,26; 11,66)

* IC is the mean confidence interval. HP-Total had an average M of 85,75 %, SP-Total of 125,71 %, and HE-Total of 64,26 % (HP-Total = HP-I + HP-II+ HP-III+ HP-IV; SP-Total = SP-I + SP-II+ SP-III+ SP-IV; HE-Total = HE-I + HE-II+ HE-III.).

The wood samples were dried in a household MW device measuring 200 mm x 300 mm x 300 mm (inner chamber), with a frequency of 2,45 GHz, maximum output power of 800 W, and homogenous energy distribution inside the chamber. Since the wood samples have a thickness of 10 mm, an MW device with 2,45 GHz was chosen because wood samples with a thickness up to 90 mm must be treated with a frequency of 2,45 GHz (Torgovnikov and Vinden 2009).

The reference moisture content for indoor wood applications of Service Class 1 is, usually, around 12 %, according to CEN EN 1995-1-1 (2004). In addition, most of the wood properties are reported at 12 % M. Therefore, the final target M after MW treatment is 12 %.

Considering the need to follow the sample's weight along the drying cycle, the MW drying comprises successive periods of MW drying and sample weight on a scale located outside the MW oven. Based on the preliminary tests and research carried out by Kol and Çayır (2021), Kol and Çayır (2022), who used 30s cooling intervals, and Ramezanpour *et al*. (2014), who used intervals of 60 to 90 s in each 60 to 150 s of MW exposure in order to avoid cracking caused by fast moisture loss from wood, the samples are cooled during these breaks, and the water vapor loss is weighted. Therefore, each treatment run lasted 30 s, followed by 60 s for cooling and homogenizing the MC of the specimens before measuring the weight. It should be emphasized that this period of 60 s enables a much more gradual release of water vapor. Then, it reduces the peak pressure value inside the sample, which leads to much lower wood damage. This break time is also enough to weigh the 6 specimens treated at a time (Figure 2).

It is noteworthy that the moisture content losses that might occur between the pauses to measure the weight of the specimens were not accounted for. However, this does not affect the results of statistical analysis of the results.

Figure 2: MW drying of the wood samples.

Once the MW treatment is completed, the water mass percent loss (WPL) can be calculated using Equation 1 (Kol and Çayır 2021).

$$WPL = \frac{w_f - w_i}{w_{od}} \; x \; 100 \qquad (1)$$

Where, *WPL* is the water weight percentage loss, in %; w_f is the weight of the sample after MW treatment, in g; w_i is the weight of the samples before MW treatment, in g.

The water absorption capacity of both MW-treated and control samples was tested by measuring the uptake of distilled water. The samples were put in an autoclave at the Chemistry Laboratory of Universidade da Beira Interior (UBI) (Figure 3) under a nitrogen pressure of 0,6 MPa. Their masses were measured at different times: 5, 15, 35, 65, and 125 min (i.e., impregnation cycles of 5, 10, 20, 30 and 60 min, totalizing 125 min). The water uptake (W) was measured by using Equation 2:

$$W(\%) = \frac{w_t - w_{bi}}{w_{od}} \; x \; 100 \qquad (2)$$

Where W is the water uptake, in %; w_t is the weight of the sample after the water impregnation at the instant in which it was measured, in g; W_{bi} is the weight of the MW-treated samples before the impregnation, in g.

Figure 3: Autoclave used for the water impregnation.

Compression strength parallel to the grain, $f_{c\ 0,12\%}$, at 12 % moisture content, was also evaluated, according to CEN EN 408 (2012), likewise done by Hermoso and Vega (2016), with wood specimens measuring 10 mm x 10 mm x 60 mm. Before the compression tests, the wood samples were conditioned at a temperature of 20 °C ± 2 °C and 65 % ± 5 % of relative humidity.

The analysis of variance (ANOVA), at a 5 % significance level, using Minitab Software (Version 18), was applied to study the effectiveness of the MW treatment to improve the water uptake and the changes in the compressive strength of Maritime Pine and *Eucalyptus* 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.

RESULTS AND DISCUSSION

The MW drying

Each wood group had different MW drying and total drying times (including the cooling periods) (Table 2). The total drying times are less than one hour, demonstrating the ease and fast of drying wood using MW. Oloyede and Groombridge (2000) found similar results for drying *Pinus caribaea* using MW energy, while the conventional kiln drying method required hours. Furthermore, Kol and Çayır (2021), Kol and Çayır (2022) obtained total drying times varying from 15 to 61 minutes for Oriental spruce (*Picea orientalis* (L.) Link.) small clear wood samples made only of sapwood with initial moisture content from 55 % to 135 %.

The more water present in the wood, the more energy is required to heat water molecules. Hence, it increases the wood's temperature, and the water turns into steam and leaves the interior of the wood. The water's heat of vaporization is around 2260,87 J/g at 100 °C.

Moreover, within a given wood sample, if the MW drying time is directly proportional to the initial moisture content, it means that the drying process is not limited by the mass transfer phenomena but instead by the energy input.

Table 2: Sample Group and MW treatment duration.

Group	Average initial MC (%)[1]	Total drying time (s)[2]	MW drying time (s)[2]
HP-I	76,17 (5,23)	1290 (22,5)	450 (7,5)
HP-II	81,82 (3,65)	1470 (24,5)	510 (8,5)
HP-III	91,06 (7,72)	1920 (32)	660 (11)
HP-IV	93,99 (9,42)	1650 (27,5)	570 (9,5)
SP-I	115,53 (2,18)	1470 (24,5)	510 (8,5)
SP-II	126,12 (1,77)	1560 (29)	600 (10)
SP-III	128,53 (0,52)	1560 (29)	600 (10)
SP-IV	132,68 (1,85)	1850 (30,5)	630 (10,5)
HE-I	56,95 (2,47)	2370 (39,5)	810 (13,5)
HE-II	63,40 (1,80)	3000 (50)	1020 (17)
HE-III	72,43 (6,03)	3540 (59)	1200 (20)

[1]Numbers in parentheses indicate the standard deviation.

[2]Numbers outside parentheses indicate drying times in seconds and those in parentheses in minutes.

Based on Table 2 and Figure 4, it was possible to notice that the heartwood of small clear *Eucalyptus* specimens requires twice the time necessary to dry compared to small clear heartwood pine samples, even though the initial moisture content of the heartwood of *Pinus* specimens is 1,3 times higher than the *Eucalyptus* one. It can be explained by the low permeability that *Eucalyptus* species have (Esteves *et al.* 2007).

Although the *Pinus* sapwood specimens had, on average, 1,5 times more initial MC than the *Pinus* heartwood samples, their drying time was, on average, the same. It demonstrates that it is easier to dry the sapwood than the heartwood. When sapwood is turned into heartwood, a variety of changes occur, such as microstructural, chemical, and anatomical characteristics, which make heartwood less permeable. Sapwood is a living tissue that serves as a water and nutrient channel. It has a high moisture content and a soft texture. However, heartwood is made up of dead cells with no physiological function and low moisture content (Jang *et al.* 2020).

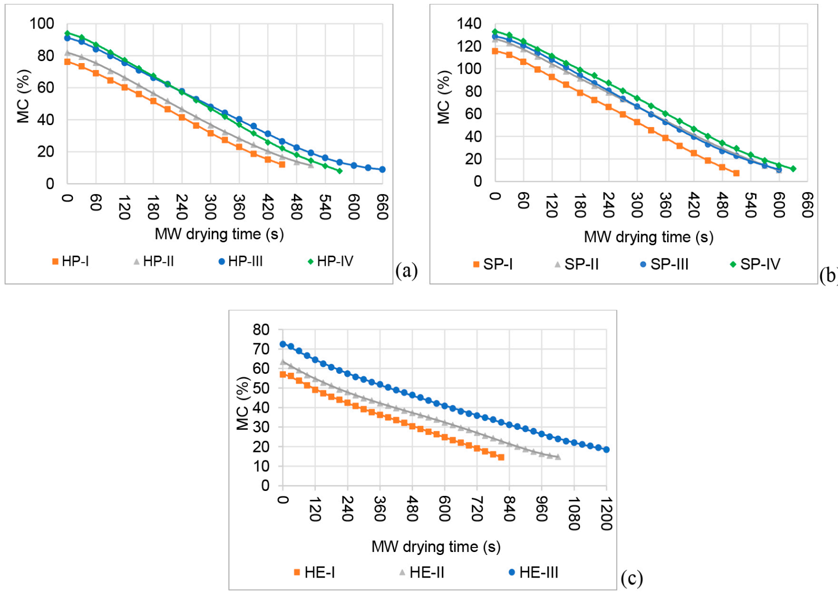

Figure 4: Average MW drying curves of eucalypts and pine wood samples. (a) Heartwood *Pinus,* (b) Sapwood *Pinus* and (c) Heartwood *Eucalyptus*

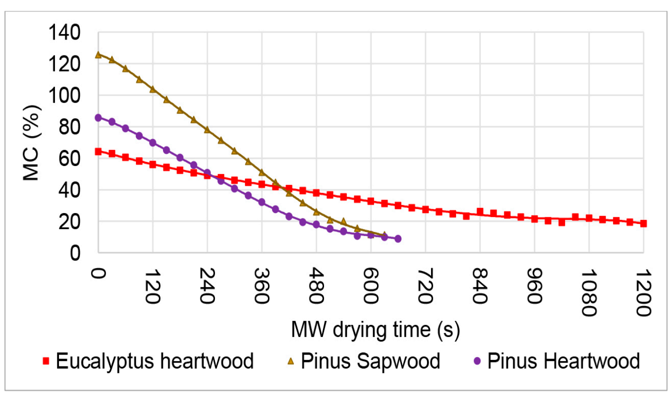

Figure 5: Average drying curves of *Eucalyptus* and pine wood samples.

Analyzing Figure 6, which shows the drying rate over the MW drying time, it is possible to see three different stages. The first three points indicate an increase in the drying rate, which might be understood as the period where some of the energy input is consumed to increase the temperature of both the water and the wood material from the ambient temperature to about 100 ºC. After that, the drying rate is constant almost until the end of the drying process. If analyzing Figure 5, the slope of the MC profile is roughly constant, indicating a constant evaporation rate, as evidenced by Figure 6. In the final stage, the last three points show a decrease in the drying rate since the amount of free water in the wood is approaching zero.

Also, analyzing Figure 6, very significant differences were observed between wood species and heartwood and sapwood when dried under similar MW conditions. It is possible to notice that the drying rates of *Eucalyptus* heartwood were the smallest ones, being around 2 and 3 times smaller than the pine heartwood and sapwood, respectively. In quantitative terms, the evaporation rate (drying rate) is about 8,27 % water/min; 3,22 % water/min for HP (pine) than HE (eucalypt), respectively. When comparing *Pinus* heart and sapwood, in quantitative terms, the evaporation rate is 8,27 % water/min and 11,50 % water/min for heartwood and sap, respectively.

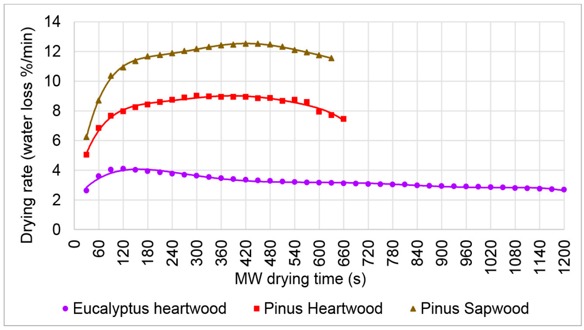

Figure 6: Average drying rates of eucalypts and pine wood samples**.**

For initial MC below the fiber saturation point (FSP), drying rates for *Pinus* heart and sapwood and *Eucalyptus* heartwood start to decrease (Figure 7), as described by Antti (1995) studying *Pinus silvestris* and *Picea abies*. Antti (1995) explains that the drying efficiency reduced as MC decreased because the greater part of energy was reflected to the magnetrons as the wood's capacity to store energy reduced. Moreover, the free water is no longer available, and the bound water, which is harder to be removed, begins to be dried.

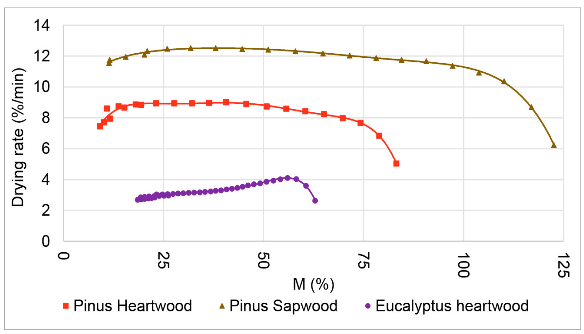

Figure 7: Effect of moisture content on drying rate.

Table 3 shows the calculated specific energy consumed by small clear wood specimens (E), the water mass percent loss (WMPL) values for MW-treated wood specimens, and the relation between energy and WMPL. MW energy/WPL means the amount of energy supplied to the wood necessary to dry 1 % of water content. WMPL values ranged from 64 to 86 % for heartwood Pinus, 108 % to 121 % for sapwood Pinus, and 42 % to 54 % for heartwood *Eucalyptus*.

The absorbed MW energy by samples during the drying process ranged from 975 MJ/m^3 to 1595 MJ/m^3. These values follow what is presented in the literature (Ganguly *et al.* 2021, Kol and Çayır 2021, Mascarenhas *et al.* 2021, Samani *et al.* 2019, Weng *et al.* 2021) for different wood species. According to Torgovnikov and Vinden (2009), to promote modifications in the wood at 2,45 GHz frequency, the values of E might be between 216 MJ/m^3 and 1550 MJ/m^3. The main modifications occur at the cellular level, damaging cell walls, pit membranes, ray parenchyma cells, and longitudinal tracheid (Weng *et al*. 2021), which end up affecting the physical and mechanical properties of wood (Mascarenhas *et al*. 2021).

Table 3: Water weight percent loss (WMPL) and specific energy consumed € values for the MW-treated samples.

Group	Average initial MC (Standard Deviation) (%)	E (MJ/m^3)	WMPL (%)	MWenergy/ WMPL (MJ/m^3/%)
HP-I	76,17 (5,23)	975	63,94	15,25
HP-II	81,82 (3,65)	1071	69,99	15,31
HP-III	91,06 (7,72)	1326	81,82	16,19
HP-IV	93,99 (9,42)	1228	85,76	14,32
SP-I	115,53 (2,18)	1416	108,06	13,10
SP-II	126,12 (1,77)	1562	116,17	13,44
SP-III	128,53 (0,52)	1551	117,99	13,15
SP-IV	132,68 (1,85)	1595	121,28	13,15
HE-I	56,95 (2,47)	829	42,46	19,53
HE-II	63,40 (1,80)	925	48,60	19,04
HE-III	72,43 (6,03)	1049	53,88	19,47

Based on the results presented in Table 3, it is possible to state some conclusions. First, not only the initial MC impacts the necessary energy supplied to the wood samples but the amount of water removed from the samples from the same groups during the drying process. For instance, when analyzing the wood samples from group HP, the bigger the water mass percent loss (WMPL), the bigger the quantity of energy absorbed to dry.

Pinus sapwood dried faster than Pinus heartwood. However, it required more energy on average (1531 MJ/m^3) than the heartwood samples (1150 MJ/m^3) because SP samples had the highest initial MC. One of the reasons the MW treatment works very well and has several applications in wet wood is because the wood has water, which interacts very well with the waves of MW due to its dielectric properties. In this sense, under the same MW treatment conditions (the same power, same MW equipment, and the same amount of wood samples to be dried by treatment round) and the same wood specie, the greater the initial moisture content of the wood, the greater the amount of energy required to evaporate water there present; thus, drying the wood. That is why, although Pinus sapwood took less time, on average, to dry than the *Pinus* heartwood, the amount of energy required to dry it was more because it had the biggest initial water content than the *Pinus* heartwood.

Although the sapwood specimens presented the highest values of the amount of energy per MW absorbed, the *Eucalyptus* specimens had the highest ratio of the amount of energy spent to dry 1% of water, on average 19,35 MJ/m^3/%. It is also important to state that HE had the smallest initial MC and the SP the highest. This fact demonstrates, once again, the low permeability of *Eucalyptus* and the difficulties that this species presents related to drying by traditional methods. Compared to *Eucalyptus* wood, whose drying process may lead to internal pressure, *Pinus* has an easy and fast drying process (Santos 2015).

It is important to highlight that the results and discussions made here were drawn based on the MW treatment of small clear specimens of Portuguese *Pinus pinaster* and *Eucalyptus globulus* so that it can be established comparisons between species and even support and encourage the development of investigations and, above all, applications on a structural and industrial scale.

Evaluation of water uptake

Since wood's permeability indicates how easily fluids flow through it (Comstock and Côté 1968), the water absorption of the MW-treated wood specimens was measured through their water uptake (W) (Table 4). It is possible to notice that the only wood group that did not present a significant difference between MW-treated and control samples was the Maritime pine sapwood. Similar results were presented by Ganguly *et al.* (2021) using Norway spruce (*Picea abies*) sapwood. It suggests that this MW treatment used had a marginal effect on the water uptake capability of sapwood.

Since sapwood's drying and permeability capabilities are better than those of heartwood (Yin *et al.* 2015), it might already present high porosity. Thus, the MW-specific energy applied to the wood specimens may not have been sufficient to create new pathways to the water flow; however, further analyses using, for example, a scanning electron microscope are necessary to study and have a big picture of the changes in wood microstructure. According to Lepage (1986) and Silva (2020), wood permeability is well related to its treatability. CEN EN 350 (2016) states that Maritime pine sapwood is easily treated, so its permeability tends to be higher.

Table 4: Water uptake (W) of the wood samples.

W (%)					
Heartwood Pinus		Sapwood Pinus		Heartwood Eucalyptus	
MW-Treated	Control	MW-Treated	Control	MW-Treated	Control
65,86^{B} (10,26)	38,91^{C} (8,05)	71,78^{A} (4,52)	71,07^{AB} (2,71)	29,25^{D} (7,19)	21,55^{E} (4,16)

The arithmetic means are shown for each wood group, and the standard deviations are the numbers in parentheses. The letters are the Tukey test results (α=0,05).

The average water impregnation rate for the MW-treated and Control heartwood *Pinus* groups were 0,60 % water/min and 0,41 % water/min, respectively. The water uptake rates for the MW-treated and Control sapwood *Pinus* groups were 0,64 % water/min and 0,68 % water/min, respectively. Finally, the water impregnation rates of MW-treated and Control heartwood *Eucalyptus* were 0,36 % water/min and 0,19 % water/min (Figure 8). These results clearly indicate that the MW treatment is particularly effective for the heartwood eucalypt, which is an expected result considering the higher basic density of the wood regarding pine and the presence of the extractives in the heartwood.

The increased absorption of distilled water observed in the MW-treated pine and *Eucalyptus* heartwood specimens can benefit their future uses and applications, whether in wood or wood-based elements. For example, this water absorption improvement increases the ease with which wood elements can be impregnated with preservative agents or resins. This reduces the number of wood and wood-based elements with defective treatments and consequent losses. Finally, opening new possibilities for manufacturing wood-based elements with enhanced properties.

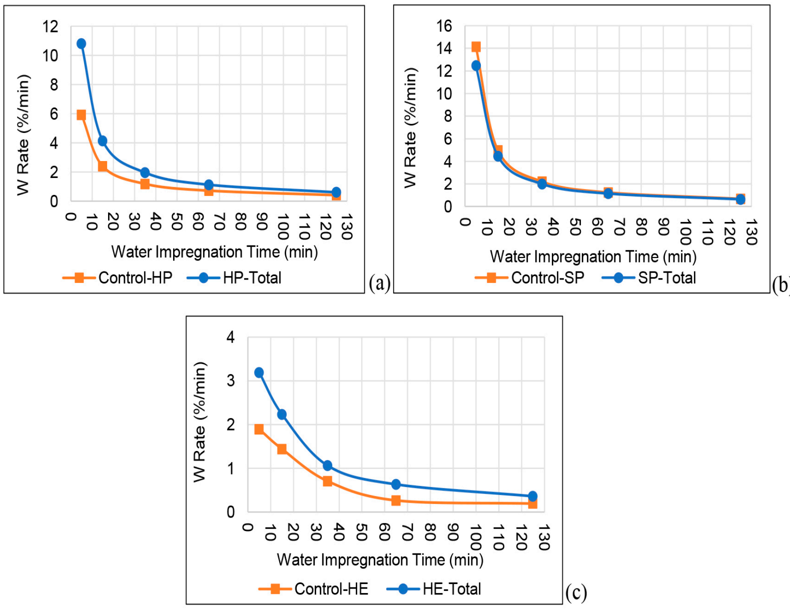

Figure 8: Water uptake (W) rate after 125 min. (a) Heartwood *Pinus,* (b) Sapwood *Pinus* and (c) Heartwood *Eucalyptus*.

Compression strength parallel to the grain f ($f_{c\ 0,12\%}$)

Table 5 presents the average $f_{c\ 0,12\%}$,the standard deviation, and the statistical analysis. Under the current MW treatment parameter, it is possible to notice that only the MW-treated *Eucalyptus* heartwood samples are statistically significantly different compared to the control group. Similar results were pointed out by Hermoso and Vega (2016).

Although *Eucalyptus* MW-treated specimens had $f_{c\ 0,12\%}$ smaller than the control group, the obtained value is the same as that of the heartwood *Pinus* MW-treated and control groups. For the sapwood *Pinus* results, Kol and Çayır (2021) and Kol and Çayır (2022) used Oriental spruce sapwood specimens and had similar results with no significant difference for $f_{c\ 0,12\%}$.

Table 5: Results of compression strength parallel to the grain, $f_{c\ 0,12\%}$.

$f_{c\ 0,12\%}$ (MPa)					
Heartwood Pinus		Sapwood Pinus		Heartwood Eucalyptus	
Control	MW-Treated	Control	MW-Treated	Control	MW-Treated
63,63 ^{B} (10,00)	62,21 ^{B} (7,18)	52,11 ^{C} (3,09)	47,60 ^{C} (2,24)	74,77 ^{A} (4,33)	60,28 ^{B} (6,60)

The arithmetic means are shown for each wood group, and the standard deviations are the numbers in parentheses. The letters are the Tukey test results (α=0,05).

CONCLUSIONS

Using small clear wood specimens and based on the MW treatment parameters used in this research, it was possible to notice that each wood species behaves differently under MW treatment. *Eucalyptus* heartwood took longer to dry than heart and sapwood pine, reflecting the low permeability of *Eucalyptus* heartwood specimens. In addition, the energy consumed by the heartwood eucalypts specimens (average initial M of 64 %) was around 935 MJ/m^3 against 1150 MJ/m^3 of heartwood pine (average initial M of 86 %) and 1531 MJ/m^3 of pine sapwood (average initial MC of 126 %).

Furthermore, analyzing the water uptake of the MW-treated and control specimens, the MW treatment with the parameters used in this paper demonstrated to be effective in improving the water impregnability of pine and eucalypts heartwood. On the other hand, pine sapwood MW-treated specimens did not have a statistically significant difference between the control ones, which might be explained due to the inherent high permeability that *Pinus* sapwood already has. Finally, MW treatment for wood modification has proved to be a viable possibility for drying and water uptake increase of both Portuguese wood species, *Eucalyptus globulus* and *Pinus pinaster*. Thus, being able to bring real and practical contributions to the field of scientific investigation, the industry, and the engineers of the wood field, such as the possibility of manufacturing wood-based products by impregnating them with resin.

Concerning the compression strength parallel to the grain, only the heartwood *Eucalyptus* presented a reduction compared to the control group. In contrast, the other groups showed no statistically significant difference between MW-treated samples and their respective control groups.

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