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THE EFFECTS OF PRE-MICROWAVE TREATMENT ON IMPREGNATION PROPERTIES AND SOME MECHANICAL PROPERTİES OF SPRUCE WOOD TREATED WITH CCA

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ABSTRACT

In this study, spruce wood speciemens were subjected to microwave (MW) pre-treatment prior to impregnation. The samples had an initial moisture content (MC) of 60% and were exposed to MW irridation in a microwave oven for 5, 5.5, and 6 min, while maintaining a constant power level of 800 W. Following the MW pre-treatment, the speciemens were impregnated with a 1.5% CCA solution using a vacuum-pressure method consisting if an initial vacuum phase of 20 min followed by a pressure stage of 30 min. Retention values and penetration depths were subsequently measured for each treatment group as well as for untreated control samples. The results indicated that MW pre-treatment significantly improved both retention and penetration performance. The retention values obtained for speciemens treated for 5, 5.5, and 6 min were 5.37, 6.04, and 6.18 kg/cm^3, respectively, whereas the control samples exhibited a retention level of 3.64 kg/cm^3. These findings demonstrate that MW pre-treatment enhances the impregnation efficiency of spruce wood. However, the treatment also led to reductions in certain mechanical properties, including modulus of elasticity (MOE), modulus of rupture (MOR), and compression strength parallel to the grain (CS).

KEYWORDS: Spruce, microwave treatment, retention, mechanical properties.

INTRODUCTION

Spruce wood is regarded as one of the most significant tree species in Turkey (OGM 2020). Nevertheless, it is generally classified as refractory species with low treatability during impregnation process (Ulvcrona 2006). This characteristic is largely related to the number and size of pit membrane pores present in its anatomical structure. During wood drying, high surface tension forces may cause the pit membranes to shift and block the pit apertures. This phenomenon is known as pit aspiration (Bolton and Petty 1997; Fujii et al. 1997). To improve the impregnation performance of refractory wood species, several modification techniques have been investigated, including steaming, mechanical incising, drilling methods, and bio-incising (Schwarze et al. 2006; Lehringer et al. 2009; Dashti et al. 2012). While these procedures can enhance preservative penetration to some extent, they may also involve additional processing steps, increased costs, or potential damage to the wood structure.

Previous investigations have demonstrated that microwave treatment enhances the permeability of wood, particularly in refractory species, thereby facilitating more efficient impregnation of preventative agents (Balboni et al. 2018; Poonia et al. 2018; Kol and Çayır, 2021; Mascarenhas et al.2021; Weng et al. 2021). Microwave (MW) technology has been widely applied in the wood industry to improve the efficiency of wood drying processes (Jang and Kang 2022). Moreover, MW treatment is considered an environmentally friendly, cost-effective, and time-saving method, as it significantly reduces processing time while simultaneously improving drying quality (Balboni et al. 2018; Mascarenhas et al. 2021; Torgovnikov and Vinden 2010; Hermoso and Vega 2016; Samani et al. 2019). When wood specimens with similar dimensions and moisture content are compared, air drying may take several days, kiln drying several hours, while microwave drying can complete the process within a few minutes (Oloyede and Groombridge 2000).

Microwave (MW) drying to pine (*Pinus sylvestris*) and spruce (*Picea abies*) wood results in two key advantages: a substantial reduction in drying duration and a decrease in potential drying-related defects (Antti 1995). In conventional wood drying techniques, heat initially penetrates the wood surface and subsequently diffuses toward the interior. In contrast, during microwave (MW) drying, electromagnetic energy is directly absorbed by water molecules and converted into thermal energy. Consequently, MW energy penetrates wood specimens rapidly, causing a quick increase in internal temperature (Zielonka and Gierlik 1999).

The aim of this study was to increase the permeability of spruce wood with MW pre-treatment to reach higher retention levels and determine the effect of absorbed MW energy due to its high moisture content. In species previously found impervious to liquids and gases, the wood permeability in the radial and longitudinal direction can be increased by a factor of thousands (Vinden et al. 2010; Torgovnikov and Vinden 2010).

EXPERIMENTAL METHODS

Preparation of wood specimens

Spruce wood used in this study was obtained from the Maçka district of Trabzon Province, Turkey. Planks with a thickness of 25 mm were prepared and subsequently cut into longitudinal specimens measuring 300 x 20 x 20 mm (L x W x T). The specimens were classified into five experimental groups (Tab. 1). Prior to MW treatment, the samples belonging to groups C1, M1, M2, and M3 were conditioned in climate chamber until they reach a moisture content (MC) of 60%. In contrast, the equilibrium MC of the control group (C1) was maintained at 12%.

Tab. 1: Experimental design.

Group	Time of MW power application [min]	MW power [W]	Preservative type	Concentration of preservative [%]
C	-	-	-	-
C1	-	-	CCA	1.5
M1	5	800		
M2	5.5			
M3	6			

Microwave treatment

A MW oven with a maximum output power of 800 W at a frequency of 2450 MHz was used for the experiment. Ten replicates were used for each group. The MW intensity was kept constant at 800 W for all groups. The wood samples (C1, M1, M2, and M3), which had 60% initial MC, were pre-treated with MW for 5, 5.5 and 6 min for all test groups.

Determination of preservative retention

Impregnation method

Before impregnation, cross sections of the MW pre-treated test samples were coated with two layers of paraffin to prevent the preservative from flowing through the longitudinal direction. Samples were then impregnated with CCA according to AWPA E10-01: 2001. Test specimens in solution were subjected to a pre-vacuum of 685 mmHg for 20 min, followed by a pressure of 8 atm for 30 min. The etention was calculated as follows:

$$R = \frac{G \times C \times 10}{V} \quad (kg/m^3) \tag{1}$$

where: R - the amount of wood preservative remained in the wood specimen, G - the weight of the preservative solution absorbed by the block (W_2-W_1) (g). C - the weight of preservative in 100 g of treating solution (g), and V is the volume of the specimen (cm^3).

The penetration depth

The penetration depth was determined according to the AWPA A3-08: 2010. Chrome Azurol S (Mordan blue) was used as a separator A solution was prepared by dissolving 0.5 g of Chrome Azurol S and 5 g of sodium acetate in 80 ml of water, which was then diluted to a total volume of 300 ml. Immediately after the impregnation process, the mixture was applied to freshly cut samples at their centers. The resulting dark blue color indicates the presence of copper. After completing the staining process, photographs of the samples were taken. Each sample was measured at 8 points (Fig. 1), using the Digimizer v.3.1.2 analysis software. The average was used to determine the penetration depth.

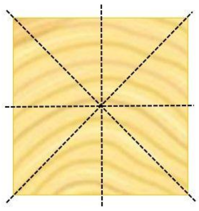

Fig. 1: Determination of penetration depth.

Mechanical properties

Modulus of elasticity and modulus of rupture

Modulus of elasticity **(**MOE) and modulus of rupture **(**MOR) were determined by 3-point bending according to TS 2478: 1976 in a universal testing equipment type Zwick. The MOE and MOR were calculated by the following formulas:

$$MOE = \frac{P \times L^3}{4 \times f \times b \times h^3} \quad N/mm^2 \qquad (2)$$

$$MOR = \frac{3 \times F \times L}{2 \times b \times h^2} \quad N/mm^2 \qquad (3)$$

where: P - the different of load (N), L - the span (mm), f - the rate of bending (mm), b - the width of the sample (mm), h - the thickness of the sample (mm), and F - the peak load (N).

The compression strength

The compression strength parallel to the grain values for control samples (untreated) and test samples were recorded at Losenhausen and on the Mohr & Federhaff Universal Test Machine according to TS 2595: 1988, calculated from the following formula:

$$CS = \frac{F_{max}}{A \times b} \quad N/mm^2 \qquad (4)$$

where: F_{max} - the force applied on wood specimen (N); A - the width of the sample (mm); and b - the height of the sample (mm).

Statistical analyses

Statistical analyses were conducted using SPSS 22 software. The retention levels and mechanical properties results of spruce wood were compared using the Duncan homogeneity test at a 95 % confidence level.

RESULTS AND DISCUSSION

Impregnation properties

The retention amounts of the samples with and without the MW treatment, along with the Duncan test results for the homogeneity of groups are given in Tab. 2. The retention level of control spruce wood (C1) is comparable to that reported in previous studies (Ramezanpour et al. 2008, Durmaz and Yıldız 2016). However, the MW pre-treatment increased the retention levels up to 69.67%. The lowest increase in retention (47.59%) was observed in the M1 group, while the highest increase was observed in the M3 group (Tab. 2, Fig. 2).

Tab. 2 : CCA Retention levels (kg.m^{-3}) and penetration depth (mm).

	Retention (kg.m^{-3})				Penetration depth (mm)			
Groups	Means	HG*	Std. dev.	Increase (%)	Means	HG*	Std. dev.	Increase (%)
C1	3.64	(A)**	0.66		4.64	(A)**	0.29	
M1	5.37	(B)	0.77	47.59	9.19	(B)	0.63	97.93
M2	6.04	(C)	0.75	65.97	10.40	(C)	0.92	124.01
M3	6.18	(C)	0.65	69.67	11.32	(D)	1.07	143.95

**: Homogeneity groups, **: Means with the same letter are not significantly different at $p < 0.05$. Comparisons were done within the each wood species group.*

Vinden et al. (2007) noted that the effect of MW pre-treatment on the retention and mechanical resistance values of Sitka spruce wood. Preservative penetration increased 3.5 to 5 times compared to control samples. Ramezanpour et al. (2015) investigated the retention levels for the MW pre-treated fir wood (*Abies alba L.*). They found that the retention levels for samples exposed to MW treatment for 16 min were enhanced about 7 times compared to control samples. Dashti et al. (2012) noted that the retention levels of the MW pre-treated wood samples increased due to improved permeability of the wood in the radial direction. The effect of MW on preservative retention may refer to the rupture of ray cell. Poonia et al. (2015) investigated the effect of MW pre-treatment for *Eucalyptus teretikornis* wood samples. They found that the retention levels increased 8 and 14 times compared to control samples. Samani et al. (2019) noted the effect of MW pre-treatment on the retention levels of *Melia composita* wood. They found that the retention levels for samples exposed to MW treatment were approximately three times higher than those of control samples. Kol and Çayır (2021) investigated the effect of MW pre-treatment on *Picea orientalis* L. wood samples. They found that the retention levels increased about 1.7 times compared to control samples. Dominik et al. (2021) investigated the retention levels for the MW pre-treated Norway spruce wood (*Picea abies* L.). They found that the retention levels increased about 3 times compared to control samples. Ganguly et al. (2025) investigated the retention levels for the MW pre-treated Norway spruce wood (*Picea abies* L.). They found that the retention levels for samples exposed to MW treatment for 16 min were enhanced about 2–2.3 times compared to control samples.

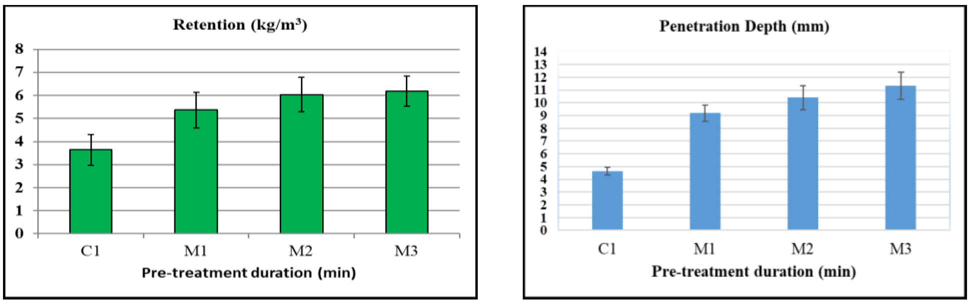

Fig. 2: CCA retention levels and penetration depth in spruce wood samples with or without MW pre-treatment.

The penetration depths of the samples with and without MW treatment, along with the Duncan test results for homogeneity of groups are given in Tab. 2. The penetration depth of control spruce wood (C1) is comparable to that reported by Ramezanpour et al. (2015) and Durmaz and Yıldız (2016). However, the MW pre-treatment increased the penetration depth up to 143.95%. The lowest increase in penetration depth (97.93%) was observed in the M1 group while the highest increase was observed in the M3 group (Tab. 2 and Fig. 2). Pictures of the distribution of the impregnation agent in samples are shown in Fig. 3.

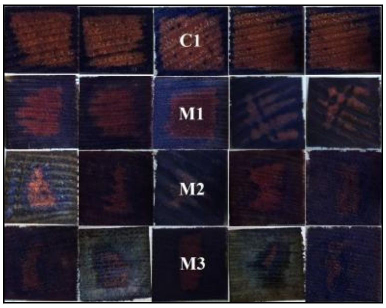

Fig. 3: CCA penetration depth.

Ramezanpour et al. (2015) investigated the penetration depth for the MW pre-treated fir wood (*Abies alba* L.). They found that the penetration depth for samples exposed to MW treatment for 16 min was approximately four times greater than that of control samples. Poonia et al. (2015) investigated the effect of MW pre-treatment for *Eucalyptus teretikornis* wood samples. They found that the penetration depth increased by about 30% compared to control samples. Dominik et al. (2021) investigated the retention levels for the MW pre-treated Norway spruce wood (*Picea abies* L.). They found that the penetration depth increased approximately twice compared to control samples.

Mechanical properties

Tab. 3 summarises the effect of MW pre-treatment at different durations on MOR, MOE and CS compared to the control groups. The mechanical resistance values of the control samples which received no treatment were consistent with the results from a previous study (Durmaz 2016). On the contrary, the MW pre-treatment reduced the mechanical resistance values. The data were statistically evaluated by one-way ANOVA to demonstrate the effect of MW pre-treatment and untreated wood samples on mechanical resistance values. Differences between the test and control groups were statistically significant at the 0.05 level.

Tab. 3: Mechanical properties values.

Groups	Modulus of rupture [N/mm^2]				Modulus of elasticity [N/mm^2]				Compression strength [N/mm^2]			
	means	HG*	Std. dev.	% Dec	means	HG*	Std. dev.	% Dec	means	HG*	Std. dev.	% Dec.
C	59.10	(A)**	4.89		2191.22	(A)**	141.25		40.95	(A)**	1.51	
C1	58.84	(A)	2.80	0.43	2187.86	(A)	90.06	0.15	41.36	(A)	3.10	-1.01
M1	54.66	(A)	3.03	7.52	1952.19	(B)	79.71	10.91	39.07	(AB)	4.05	4.58
M2	53.45	(AB)	5.15	9.55	1867.10	(B)	141.09	14.79	38.61	(AB)	4.81	5.70
M3	48.43	(B)	5.98	18.06	1855.09	(B)	105.10	15.34	36.16	(B)	4.02	11.70

**: Homogeneity groups, ** : Means with the same letter are not significantly different at $p < 0.05$. Comparisons were done within the each wood species group.*

MOR values for M3 decreased by about 18.06% compared to control spruce wood samples (C). The results showed a significant difference between the control and M3 groups. However, there were no singificant differences among the C, C1, M1 and M2 groups (Fig. 4).

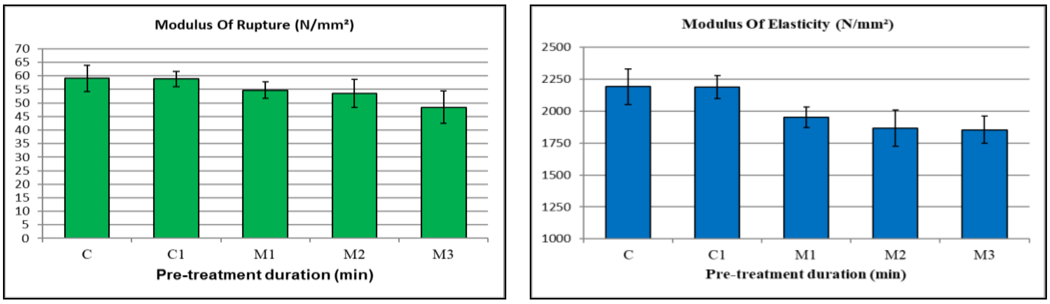

Fig. 4: MOR and MOE in spruce wood samples with or without MW pre-treatment.

Oloyede and Groombrige (2000) examined the effect of MW pre-treatment on Carribean pine. They found that the loss of MOR was about 17%. Hansson and Antti (2003) investigated the impact of MW pre-treatment of Norway spruce. They reported a decrease in MOR compared to control samples. Vinden et al. (2007) investigated the effect of MW pre-treatment on the retention and mechanical resistance values of Sitka spruce. They presented that the loss in MOR was about 30%. Kol and Çayır (2021) investigated the effect of MW pre-treatment on *Picea orientalis* (L.). It was stated that the loss in MOR was about 6.1%.

MOE decreased from an average of 2191.22 N/mm^2 for untreated spruce wood to an average of 1855.09 N/mm^2 for M3 impregnated spruce wood MW samples. The results showed significant differences in MOE values between the control wood samples (C and C1) and the MW-pre-treated spruce wood samples. However, there was no significant difference among M1, M2 and M3 groups. The highest decrease in MOE values for the MW pre-treated spruce wood for 6 min was about 15.34% (Fig. 4).

Oloyede and Groombrige (2000) reported this remedial effect of Carribean pine caused by MW treatment. They showed that the loss in MOE was about 31%. Hansson and Antti (2003) investigated the impact of MW pre-treatment of Norway spruce. They reported a decrease in MOE compared to control samples. Vinden et al. (2007) noted the effect of MW pre-treatment on the retention and mechanical resistance values of Sitka spruce wood. They stated that the loss in MOE was about 30% for the wood samples exposed to MW pre-treatment compared to control samples. Kol and Çayır (2021) investigated the effect of MW pre-treatment on *Picea orientalis* (L.). It was stated that the loss in MOE was about 6.2%.

Tab. 3 summarises the effect of MW pre-treatment at different durations on CS compared to the control groups. The MW pre-treatment reduced the CS values. There was no significant difference among the M1, M2 and M3 groups while a significant difference was observed between the M3 and control groups. The highest decrease in CS for MW-pre-treated spruce wood samples after 6 min was approx. 11.70% compared to the control samples (Fig. 5).

Machado (2006) investigated the effect of MW pre-treatment on oak. It was stated that the loss in CS was about 10%. Kol and Çayır (2021) noted the impact of MW pre-treatment on *Picea orientalis* (L.) wood. It was stated that the loss in CS was about 2.9%.

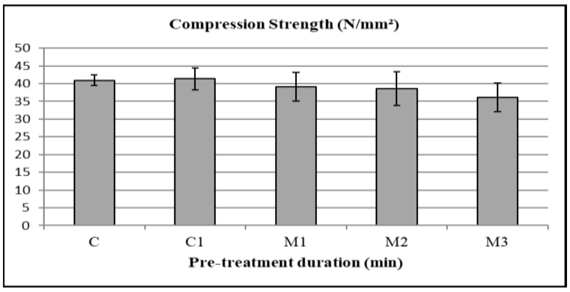

Fig. 5: CS in spruce wood samples with or without MW pre-treatment.

CONCLUSIONS

The results of this study indicated that the MW pre-treatment increased the retention levels and penetration depth at 69.67%, 143.95%, resp. However, the mechanical resistance of spruce wood decreased with increasing exposure to MW pre-treatment durations. The retention levels and penetration depth increased as microwave pretreatment time increased. The reason for the increase in retention levels and penetration depth can be explained by the fact that pit aspiration and weak ray cells in spruce wood may cause deformation due to MW pre-treatment. As microwave pre-treatment time increased, the mechanical properties (MOR, MOE and CS) of spruce wood decreased up to 18.06%, 15.35%, 11.70%, resp. The reason for the decrease in mechanical properties of MW pre-treated spruce wood could be due to the cracks that occurred in the wood samples during the MW treatment.

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