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STEAMING TREATMENT DECREASES MOE AND COMPRESSION STRENGTH OF TURKEY OAK WOOD

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ABSTRACT

This study examined the mechanical properties of Turkey oak (*Quercus cerris* L.) wood before and after combined steam and thermal treatments under vacuum conditions. Wood was steamed at 100 to 110°C and thermally treated under vacuum at 160°C by the press-vacuum or thermo-vacuum process. Treated material was characterized in terms of the modulus of elasticity (MOE) and compression strength of heartwood and sapwood. The MOE was established using a nondestructive technique based on the measurement of ultrasonic pulse propagation. Results differed depending on the treatment or combination of treatments, and showed that the steaming process strongly affected the MOE. Thermo-vacuum treatment increased the compression strength, whereas steaming had the opposite effect.

KEYWORDS: *Quercus cerris* L., hydrothermal, thermo-vacuum, modulus of elasticity, compression strength.

INTRODUCTION

The low potential of Turkey oak (*Quercus cerris* L.) wood is inherently linked to its poor dimensional stability, elevated internal tension, low durability, and strong propensity to swelling and shrinking (Giordano 1981). Technological properties of Turkey oak wood can be improved through heat and steam treatments (Todaro 2012; Todaro et al. 2012), which cause both chemical and physical changes. Heat transfer tends to improve the durability and reduce the shrinking and swelling of wood, whereas steaming is one of the main methods for homogenizing the color of wood and preventing defects due to growth stresses (Hill 2006). Recently, Todaro et al. (2012, 2013) reported promising results concerning the possible improvement of Turkey oak wood properties by hydrothermal treating, which could represent a good solution for enabling new industrial applications (i.e., parquetry).

Mechanical properties of wood are evaluated through different techniques. Aside from destructive techniques, nondestructive techniques based on ultrasonic wave methods, stress waves, and transverse vibration are available. One of the most important mechanical characteristics, the modulus of elasticity (MOE) measures the stiffness and indicates the strength of wood. Kollmann and Côté (1968) reported a high correlation of MOE to the ultimate strength of wood in bending. Other studies showed a high correlation between the dynamic and static MOE (e.g., Pellerin 1965; Divós and Tanaka 2005).

Studies on the influence of thermal treatment reported a slight increase in MOE when wood is thermally treated for a short time period (Hill 2006). Using a vibrational treatment method, Kubojima et al. (1998) reported an increase of the MOE of *Picea sitchensis* in the first 2 hours of treatment, followed by a constant value for wood treated at 120 and 160°C. However, contrasting evidence found by Volkmer et al. (2014) highlighted the negligible influence of heat pressure steaming on MOE for Common oak (*Quercus robur* L.).

The aim of the present work was to investigate the mechanical behavior of Turkey oak wood when treated through combined steam and thermal processes under two vacuum conditions. We hypothesized that the different treatment types (steaming and/or heating) could have different effects on the MOE and compression strength of Turkey oak wood. We also evaluated the different responses of MOE and compression strength between sapwood and heartwood.

MATERIAL AND METHODS

Wood was harvested from four logs (3 m in length) derived from four trees (40 cm in diameter at breast height) in the Apennine Mountains of the Basilicata Region of Southern Italy. Logs were then spitted in two parts and one of them was steamed (S) under saturated conditions for 24 h at a maximum temperature and pressure of about 110°C and 140 kPa, respectively. Logs were cooled for 5 days in the same chamber after treatment and dried to a moisture content of 0 %.

After steaming process, three boards without defect were obtained from each log (a total of 12 steamed and 12 unsteamed boards) measuring 250 × 20 × 1400 mm (tangential × radial × longitudinal). Then, on a subsample of 16 boards (eight boards per treatment), drying and thermal treatments were performed in the same apparatus without any time interruptions. Thermal treatment was done by two different processes: a press-vacuum process (PVP) and a thermo-vacuum process (TVP). These processes were developed by the Italian company WDE Maspell s.r.l. and described by Ferrari et al. (2013). Wood was dried under vacuum (200–230 mbar) at low temperatures to avoid internal cracks, which are very frequent in Turkey oak. At the beginning of the treatment, the air temperature was increased until the set value (160°C) was reached. The temperature was kept constant for 3 hours under a pressure of 200–230 mbar. After thermal treatment, a cooling phase was conducted. The summary of treatments is provided in Fig. 1.

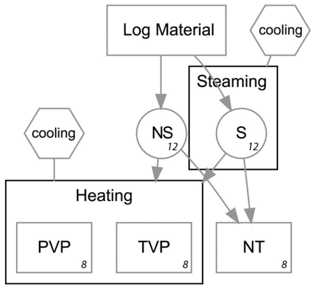

Fig. 1: Diagram of the treatment pattern. NS = not steamed; S = steamed; NT = not thermo-vacuum treated; PVP = thermo-vacuum treated with press-vacuum technology; TVP = thermo-vacuum treated with Termovuoto® technology. Italicized numbers on the node are the sample depth.

Tab. 1 describes the experimental steps of the treatments. For more detail, the reader is directed to the 2013 article by Ferrari et al. (2013).

Tab. 1: Phases and specifications of treatments for Turkey oak wood.

Phase	Specifications
Harvest	4 logs from 4 trees
Steaming	110°C/24 h with pressure of 140 kPa
Board preparation	Steamed and unsteamed logs were cut into 40-mm-thick boards
Seasoning	5 months, moisture content of 20–25 %
Board selection	24 boards without defects; 4 logs per steaming/heating treatment
Artificial drying	To a moisture content of 0 %
Thermo-vacuum treatment	160°C × 3 h
Material characterization	270 measurement of MOE, 45 for each treatment

Characterization tests

Wood material was characterized to determine the effects of steaming and thermal treatments based on the MOE and compression strength. To minimize variability, all wood properties were measured and compared by matching samples cut from the same board that, after drying, was sawn into two parts (thermally treated and untreated control materials). Sawn boards were conditioned in a climatic chamber at 20°C and 65 % relative humidity (RH) for 45 days, and then cut into samples for mechanical tests.

The MOE of the boards was evaluated by the Microsecond Timer (Fakopp Enterprise, Agfalva, Hungary), with a resonance frequency of 23 kHz on both heartwood and sapwood. This device measures the stress wave velocity in the fiber direction of wood samples through a transducer pin that is placed at a distance of 1 m with an angle of 45°. At least 20 measurements of sapwood and 20 measurements of heartwood were performed on each board sample. The dynamic MOE was calculated by the Christoffel equation, $MOE = \rho * V^2$, where MOE is the dynamic modulus of elasticity ($N \cdot mm^{-2}$), ρ is the density of the specimen at a given moisture content ($kg \cdot m^{-3}$), and V is the velocity of sound propagation ($m \cdot s^{-1}$).

Compression strength was determined according to UNI-ISO 3787 (1985). Sawn boards were conditioned in a climatic room at 20°C and 65 % RH for 45 days. Boards were cut into samples of 20 × 20 × 40 mm (tangential × radial × longitudinal) for compression strength tests.

The same number of samples was randomly selected among the five treatments and the control, resulting in 482 clear wood samples (255 sapwood and 227 heartwood samples).

To test the effect of steaming and heating on the characteristics of Turkey oak wood samples, analysis of variance (ANOVA) with nested design (i.e. wood type factor nested in heat treatment factor nested in steaming treatment factor) was performed. Prior to analysis, data was tested for normality of the residuals and homoscedasticity with the Shapiro-Wilk test and Levene's test, respectively. The post-hoc was performed by TukeyHSD multiple comparison procedures to determine significant difference between means. Welch correction for nonhomogeneity of variance was also applied. For each test the level of probability was set at $p < 0.05$. All analyses were performed with R statistical suite (R Development Team 2013).

RESULTS

Analysis of variance (ANOVA) revealed a significant overall effect of steaming and heating treatment on both modulus of elasticity (MOE) and compression strength (Tab. 2).

In particular, the S-TVP treatment produced the lowest values of MOE, followed by the S-PVP and S-NT treatments (Fig. 2). Treatments without a steaming process (NS-TVP, NS-PVP) showed the highest values of MOE, which were not statistically significant compared to the MOE values of the control (NS-NT).

Tab. 2: Nested ANOVA summary table of MOE and compression strength by steaming, heating and wood type.

	MOE				
	df	SS	F	p-value	
Steaming	1	1.63E+09	983.017	2.00E-16	***
Heating	2	7.68E+07	23.134	5.74E-10	***
Steaming: heating	2	8.35E+07	25.179	1.03E-10	***
Steaming: heating:woodtype	6	4.02E+07	4.036	0.000695	***
Residuals	258	4.28E+08			
	Compression strength				
Steaming	1	29486	477.446	2.00E-16	***
Heating	2	4628	37.47	7.97E-16	***
Steaming: heating	2	1141	9.236	0.000116	***
Steaming: heating:woodtype	6	36760	99.206	2.00E-16	***
Residuals	470	29026			

SS: sum of square; df: degrees of freedom; woodtype: heartwood and sapwood. Stars indicate statistically significant differences for $p < 0.01$ (**) and $p < 0.001$ (***).

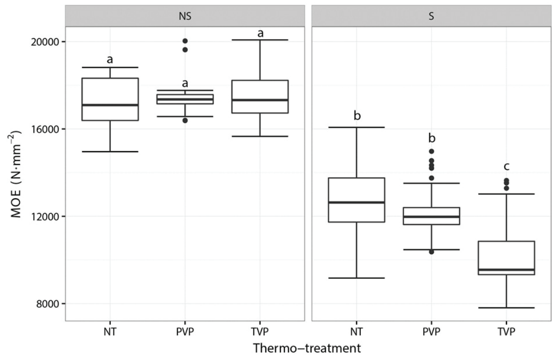

Fig. 2: Boxplot of modulus of elasticity (MOE) of Turkey oak wood after treatment. The bold line represents the median, the boxes represent the interquartile range (IQR) of the values, the top whisker is the upper quartile (+1.5 × IQR), and the bottom whisker is the lower quartile (-1.5 × IQR). The circles outside the boxes represent outliers. NS = not steamed; S = steamed; NT = not thermo-vacuum treated; PVP = thermo-vacuum treated with pressure-vacuum technology; TVP = thermo-vacuum treated with Termovuoto® technology. The same letters means no statistical significance for p<0.05.

Compression strength parallel to the fiber increased significantly after the thermo-vacuum treatment (NS-PVP and NS-TVP) compared to the untreated wood (NS-NT) and decreased significantly after the steaming process (S-PVP, S-TVP, S-NT), as reported in Fig. 3. Wood treated by the NS-PVP treatment showed a slight elevation of the compression strength compared to the control (NS-NT), perhaps due to the densification effect induced by the press-vacuum technology.

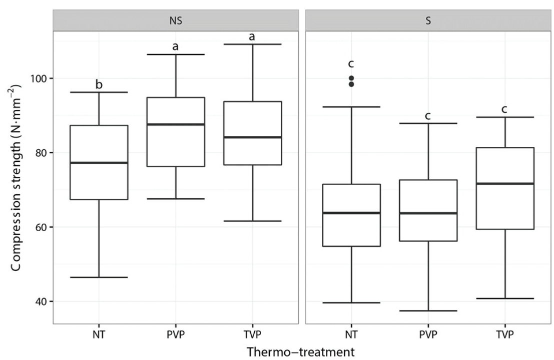

Fig. 3: Boxplot of compression strength of Turkey oak wood after treatment. The bold line represents the median, the boxes represent the interquartile range (IQR) of the values, the top whisker is the upper quartile (+1.5 × IQR), and the bottom whisker is the lower quartile (-1.5 × IQR). The circles outside the boxes represent outliers. NS = not steamed; S = steamed; NT = not thermo-vacuum treated; PVP = thermo-vacuum treated with pressure-vacuum technology; TVP = thermo-vacuum treated with Termovuoto® technology. The same letters means no statistical significance for p<0.05.

Interesting results for MOE and compression strength were observed by comparing sapwood and heartwood samples (Tab. 3). Significant differences in compression strength between sapwood and heartwood were found for all treatments, and significant differences in MOE between sapwood and heartwood were found for S-NT, S-TVP, and NS-NT. No statistical difference between the sapwood and heartwood samples was found for the S-PVP, NS-PVP, or NS-TVP treatment. Almost all MOE and compression strength results were higher for heartwood compared to sapwood (Tab. 3).

Tab. 3: Differences in modulus of elasticity (MOE) and compression strength between sapwood (SW) and heartwood (HW).

		MOE ($N \cdot m^{-2}$)				Compression ($N \cdot m^{-2}$)			
Treatment	**Wood type**	**Mean**	**S.D.**	**count**	***sign***	**Mean**	**S.D.**	**count**	***sign***
S-PVP	SW	12028.1	1134.8	22	*n.s.*	58.8	7	40	***
	HW	12442.1	1068	23		74	8.7	32	
S-NT	SW	12568.9	1227.3	22	**	54.6	6.3	50	***
	HW	13269.2	1950.2	23		73	8.9	49	
S-TVP	SW	9832.1	584	22	**	61.3	10.6	37	***
	HW	11013.5	2436.6	23		78.6	6.8	39	
NS-PVP	SW	17619.1	1032.2	22	n.s.	77.7	7.2	32	***
	HW	17205.4	460.6	23		94.1	6.5	33	
NS-TVP	SW	17105.5	910	22	n.s.	77.2	8.3	44	***
	HW	17795.2	1277.1	23		94.4	7.7	32	
NS-NT	SW	16063.2	893	22	***	68	0	51	***
	HW	17478.5	1008.8	23		87.5	6.7	43	

Stars indicate statistically significant differences for $p < 0.01$ (**) and $p < 0.001$ (***); *n.s* indicate not significant differences.

DISCUSSION

The MOE and compression strength results provide substantial insights into the mechanical properties of Turkey oak wood. The main differences in these parameters between treatments could be attributed to the steaming process. Indeed, the MOE and compression strength values of steamed samples were significantly lower than those of the unsteamed samples.

This behavior may be attributed to the well-known effects of steaming on the main components of wood, such as lignin, cellulose, and hemicelluloses. In particular, lignin is one of the main wood components responsible for a material's mechanical strength, and modification of this component could underlie the change of mechanical properties (Cao et al. 2012, Ferrari et al. 2013). The steaming of wood materials results in plasticization (Angelski 2014), by promoting hydrolysis and creating conditions favorable for lignin condensation, especially in green wood (Stamm 1956). Stamm (1956) and Sundqvist (2004) highlighted the importance of the moisture content of wood during steaming, reporting that noticeable changes in lignin structure occur at around 100 and 120°C, respectively. Compounds other than lignin also may influence the MOE and compression strength in different ways. For example, heat treatment has been demonstrated to decrease the hemicellulose content of wood significantly (Esteves and Pereira 2009). Because of its low molecular weight, hemicellulose first degrades, followed by an increasing of the crystallinity index of the cellulose (Weiland and Guyonnet 2003) and alterations of the mechanical properties.

Researches regarding mechanical properties, induced by hydro-thermo treatments, in sapwood and heartwood are lacking for Turkey oak wood despite the significant evidence found by Todaro et al. (2012, 2013) in terms of lignin, extractives, color variation, etc. As expected, our results highlight that the treatments had different influences on the MOE and compression strength of sapwood vs. heartwood. The different mechanical behaviors between sapwood and heartwood could be attributed to differences in the physical and chemical characteristics between the two parts of wood, which affect their technological performances (Todaro et al. 2013). Schowalter et al. (1998) reported that the concentration of cellulose in oak is 0.52 ($g \cdot g^{-1}$) in sapwood and 0.46 ($g \cdot g^{-1}$) in heartwood, with similar findings being reported by Ritter and Fleck (1923) for white oak. Higher lignin content in the heartwood than in the sapwood has been observed. In the present study, the absence of a statistical difference between S-PVP, NS-PVP, and NS-TVP might indicate a heat treatment effect on reducing the divergence in MOE between sapwood and heartwood.

CONCLUSIONS

Hydrothermal treatment offers a possible approach for improving the mechanical properties and, thus, the quality of Turkey oak wood. Nevertheless, the steaming process can introduce some unwanted consequences in terms of mechanical properties. Degradation or modification of the main wood components (cellulose, hemicelluloses, and lignin), which occurs mainly during the steaming stage, might have a significant effect on the MOE and compression strength of treated wood. The results obtained in this study highlight that the steaming of Turkey oak wood might decrease the MOE and compression strength values compared to heating alone, providing important information for the industry with regard to the mechanical behavior of the wood.

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