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Assessment of compressive strength and compressive modulus parallel to the grain of oak and tauari wood after thermo-mechanical modification

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Abstract: *Assessment of compressive strength and compressive modulus parallel to the grain of oak and tauari wood after thermo-mechanical modification.* European oak and tauari wood were subjected to thermo-mechanical modification. One treatment cycle consisted of three stages: heating the wood in a hydraulic press; wood densification; and cooling the wood samples in unheated hydraulic press without exerting pressure. The treatment temperature was 100 °C or 150 °C. The modification temperature significantly affected the compressive strength parallel to the grain of oak and tauari wood. Such dependencies were not found in the case of compressive modulus of elasticity parallel to the grain of tested wood species. The compressive strength of tauari wood modified at 100 °C and 150 °C was, respectively, 16% and 20% greater than the compressive strength of oak wood modified at the same temperatures. The compressive strength parallel to the grain of the oak and tauari wood depended linearly on wood density and load.

Keywords: compressive strength parallel to the grain, densification, European oak, pressing, tauari, thermo-mechanical modification

INTRODUCTION

Thermo-mechanical modification is usually carried out in a hydraulic press with heated plates (Kurowska et al. 2010; Laine et al. 2013; Bekhta et al. 2014a, 2014b; Laine et al. 2016). Methods of continuous wood densification by using rolls have also been developed (Gaff and Gašparik 2015). The machines are often modified in order to enable e.g. the introduction of steam during the treatment. This makes it possible to soften the cell walls prior to compression (Kutnar et al. 2009; Fang et al. 2012; Pařil et al. 2014).

Thermo-mechanical modification is applied to both low and high density wood (Rautkari et al. 2010; Kutnar and Kamke 2012; Tu et al. 2014; Gašparik et al. 2016; Laskowska 2017). Research involves wood from different climatic zones. Tropical zone wood is characterized by more complex anatomical and chemical structure than wood from the temperate zone. A typical feature of many wood species from the tropical zone is their irregular fibres arrangement which has significant negative impact on the wood's mechanical properties. Moreover, tropical zone wood possesses more parenchyma (Richter and Dallwitz 2000; Wagenführ 2007), which may likewise significantly affect the course of thermo-mechanical modification.

The literature contains a number of publications concerning research into the impact of technological parameters of thermo-mechanical modification, chiefly on the physical properties of wood. The most frequently described wood properties are set recovery, density profile, surface properties (Kutnar et al. 2009; Candan et al. 2010; Rautkari et al. 2010; Laine et al. 2016). Among the mechanical properties of thermo-mechanically modified wood, the most frequently analysed is hardness (Fu et al. 2016, Gašparik et al. 2016; Laine et al. 2016). Data on compressive strength and compressive modulus parallel to the grain of thermo-mechanically modified wood are scarce. As compressive strength parallel to the grain and bending strength are major factors in the work of such building elements as floors or beams, it is important to analyse these issues. It is to such materials that the thermo-mechanical modification is dedicated.

The main objective of the research has been to determine the impact of thermo-mechanical modification on the compressive strength and compressive modulus parallel to the grain of wood species from temperate climate zone (oak) and tropical zone (tauari). Tauari is similar to oak in terms of colour and wood figure. The wood species selected for research are widely used in manufacturing floors, furniture and interior furnishings.

MATERIAL AND METHODS

European oak (*Quercus robur* L.) and tauari (*Couratari spp.*) wood samples with the dimensions of 130 mm (longitudinal) × 80 mm (tangential) × 8.50 mm (radial) were used for the study. 20 samples were used for each variant of thermo-mechanical modification. Samples without visible defects were selected. Surfaces of wood samples finished by planing. After the samples were conditioned in a normal climate (temperature 20 °C ± 2 °C, relative humidity 65% ± 5%) to an air-dry condition, the moisture content of the wood was determined according to ISO 13061-1 (2014). The moisture content of the wood subjected to thermo-mechanical densification was 7.92% (± 0.68%). The density of the wood was determined using the stereometric method in accordance with the ISO 13061-2 (2014) standard requirements.

Thermo-mechanical modification consisted of three stages. At the first stage the wood was contact-heated in a hydraulic press and then densified at a unit pressure of 45 N/mm^2. The wood was cooled in a hydraulic press, whose plates were not heated, in a normal climate (temperature 20 °C ± 2 °C, relative humidity 65% ± 5%). The temperature of the platens of the press was 100 °C or 150 °C. The heating time and wood densification time were 120 s. The time of cooling the wood in hydraulic press was 240 s. The wood samples were conditioned in a normal climate for 7 days. The compression ratio (*CR*) was calculated according to Eq. 1, where t_o is the original thickness (mm), and t_d is the thickness of wood after densification (mm).

$$CR = [(t_o - t_d) / t_o]\cdot 100\ (\%) \qquad (1)$$

The compressive strength parallel to the grain (*CS*) of oak and tauari wood were carried out in accordance with ISO 13061-17 (2017), with minor alterations. It resulted from the size of the wood samples used for thermo-mechanical modification. The samples used for testing the compressive strength parallel to the grain were 10 mm long and 10 mm wide. The thickness of control samples was 8.66 (±0.12) mm, and that of modified samples corresponded to the thickness of samples after thermo-modification. The compressive strength parallel to the grain research was carried out by using a computer program coupled with Instron® testing machine, model 3382 (Norwood, USA). Using the LVDT displacement sensor, it was possible to automatically calculate the compressive modulus. The wood properties were determined for 12 control samples and for each variant of thermo-mechanical modification of oak and tauari wood. Statistical analysis was performed using STATISTICA version-12 software of StatSoft, Inc. (Tulsa, USA). The statistical analysis of the results was carried out at a significance level of 0.05.

RESULTS AND DISCUSSION

The compression ratio (CR) of oak wood densified at 100 °C and 150 °C was 32% and 38%, respectively. Whereas the CR of tauari wood densified at 100 °C and 150 °C was 30% and 35%, respectively (Fig. 1a). The density of non-densified oak and tauari wood were 651 kg/m^3 ± 35 kg/m^3 and 694 kg/m^3 ± 41 kg/m^3, respectively. The oak and tauari density values were close to literature data (Wagenführ 2007; Kozakiewicz 2012; CIRAD 2012). The density of oak wood densified at 100 °C and 150 °C was higher by 56% and 58%, respectively, than that of non-densified oak wood. The density of tauari wood densified at 100 °C was 40% higher than that of non-densified tauari wood, whereas the tauari densified at

150 °C showed 58% higher density than non-densified tauari wood. The modification temperature at level 100 °C had greater impact on the density of oak wood than on the density of tauari wood (Fig. 1b). This is due to the anatomical structure of the wood (Schrepfer and Schweingruber 1998; Navi and Girardet 2000; Wagenführ 2007; Dogu et al. 2010; Laine et al. 2016). It should be assumed that thin-walled vessels in the earlywood area of oak (ring-porous structure), with lower processing temperatures were already more susceptible to compression than tauari wood (diffuse-porous structure).

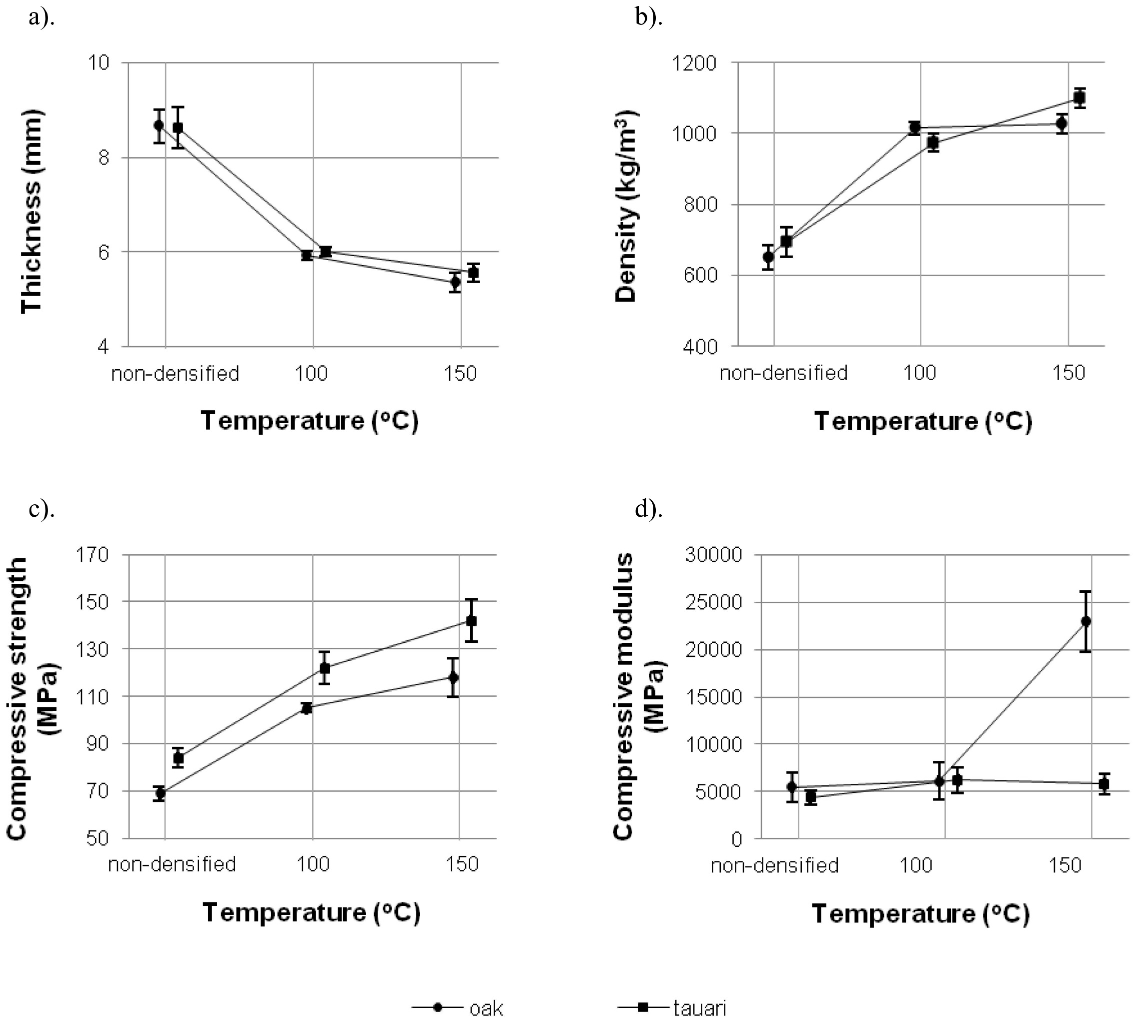

Figure 1. Thickness (a), density (b), compressive strength parallel to the grain (c), compressive modulus parallel to the grain (d) of thermo-mechanically modified oak and tauari wood

The compressive strength parallel to the grain (CS) of non-densified oak and tauari wood were 69 MPa ± 3 MPa and 84 MPa ± 4 MPa, respectively. The oak and tauari CS values were close to literature data (Wagenführ 2007; Kozakiewicz 2010; CIRAD 2012). The studies conducted show that the higher the temperature of the press platen (densification temperature), the higher the CS of wood (Fig. 1c). The CS of oak wood modified at 100 °C and 150 °C was higher than its CS before densification by 52% and 71%, respectively. Whereas the CS of tauari wood modified at 100 °C and 150 °C was higher than its CS before densification by 45% and 69%, respectively. It is worth noting that the CS of tauari wood modified at 100 °C and 150 °C was, respectively, 16% and 20% greater than the CS of oak wood modified at the same temperatures. Such dependencies were not found in the case of compressive modulus of elasticity (CM). Only oak wood densified at 150 °C had a greater

CM value (Fig. 1d). The CM of oak wood modified at 150 °C was 4 times higher than its CM before densification. Ülker et al. (2012) stated that the densification process increased compression strength of Scots pine wood (*Pinus sylvestris* L.). Authors found that it is necessary to densify Scots pine at temperatures of 120 °C or 140 °C for higher compression strength (an increase of 32 - 47%).

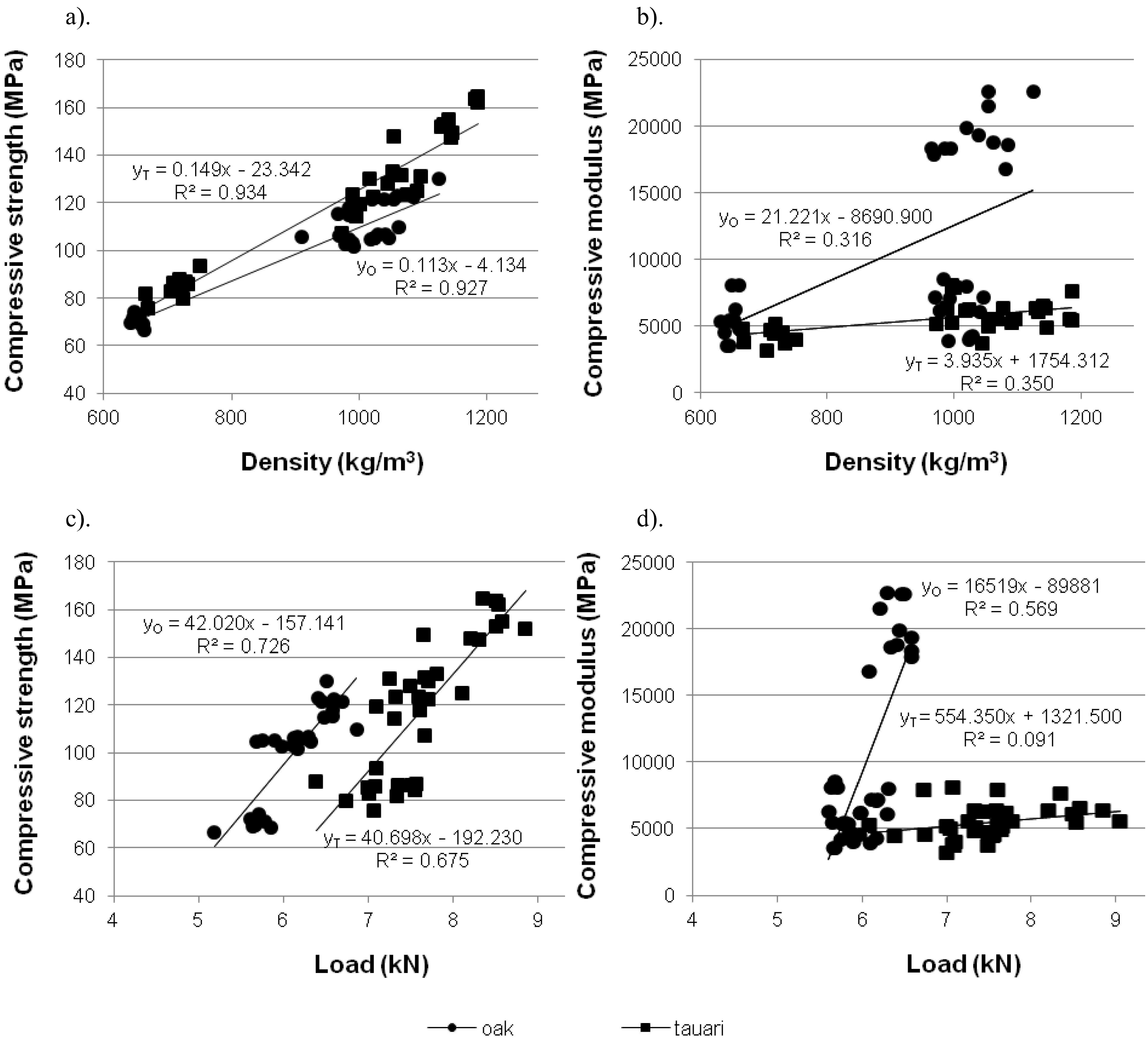

Figure 2. Relationship between selected properties of thermo-mechanically modified oak and tauari wood

Irrespective of the temperature of densification, the CS of the oak and tauari wood depended linearly on wood density (Fig. 2a). This is described in the y_O equations for oak wood and y_T equations for tauari wood. In this case, the values of the R^2 coefficient for the oak and tauari wood were high, reaching 0.927 and 0.934, respectively. The most of densified samples were damaged by “cutting”. The crack lines were skew in respect to longitudinal axis of specimens (according to ASTM D143:2014). The observed type of damages is characteristic for wood of high density (Kozakiewicz 2010). Much lower R^2 values were recorded for the CM of the wood. They were, respectively, 0.316 and 0.350 for the oak and tauari wood (Fig. 2b). The greater the density of the material under examination, the greater was the CS for oak and tauari. This shows that the mechanical properties of the material under examination depend, to a considerable extent, on the physical properties of wood, i.e. its density (Kloiber et al. 2015).

A linear relationship between the CS of densified oak wood and load (R^2 = 0.726) has been demonstrated as part of the tests. These dependencies have also been found for tauari wood (R^2 = 0.675) (Fig. 2c). In the case of the CM of wood, the dependencies were not so clear (Fig. 2d).

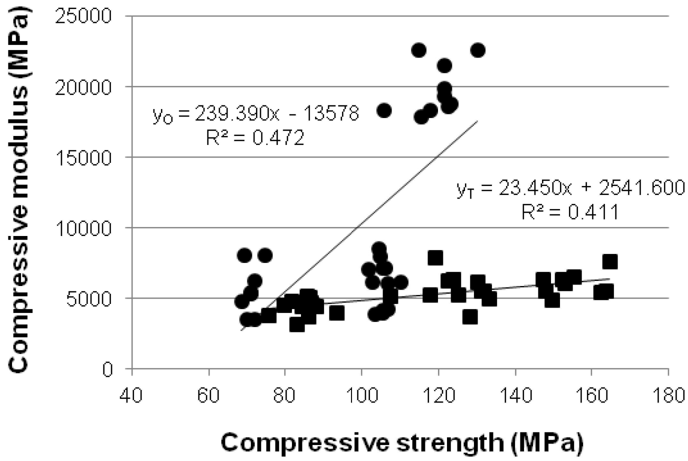

Figure 3. Relationship between compressive strength parallel to the grain and compressive modulus

The compressive modulus depends on the wood density, but also on the length and arrangement of the structural elements in the wood, as well as the compressive strength parallel to the grain (Kozakiewicz 2010; Kloiber et al. 2015). This is probably why the obtained relationship between the compressive modulus and the compressive strength parallel to the grain (Fig. 3) was greater than between the compressive modulus and the wood density (Fig. 2b).

CONCLUSIONS

1. The modification temperature significantly affected the compressive strength parallel to the grain of oak and tauari wood after thermo-mechanical densification. The higher the modification temperature, the higher the compressive strength of wood.
2. The modification temperature, at level 100 °C, had greater impact on the density of oak wood than on the density of tauari wood.
3. The compressive strength parallel to the grain of tauari wood modified at 100 °C and 150 °C was, respectively, 16% and 20% greater than the compressive strength of oak wood modified at the same temperatures.
4. Irrespective of the temperature of densification, the compressive strength parallel to the grain of the oak and tauari wood depended linearly on wood density and load. The dependencies were not so clear for studied compressive modulus.

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Streszczenie: *Ocena wytrzymałości na ściskanie i modułu przy ściskaniu wzdłuż włókien drewna dębu i tauari po modyfikacji termo-mechanicznej.* Drewno dębu i tauari poddano obróbce termo-mechanicznej. W pierwszym etapie drewno ogrzewano kontaktowo w prasie hydraulicznej, następnie zagęszczano, po czym poddawano chłodzeniu w nieogrzewanej prasie hydraulicznej bez użycia ciśnienia. Temperatura półek prasy, przy której prowadzono proces zagęszczania drewna wynosiła 100°C lub 150°C. Temperatura obróbki wykazała istotny wpływ na wytrzymałość na ściskanie wzdłuż włókien drewna dębu i tauari. Zależności tych nie stwierdzono w przypadku modułu przy ściskaniu wzdłuż włókien badanych gatunków drewna. Wytrzymałość na ściskanie drewna tauari zagęszczanego w temperaturze 100°C i 150°C była odpowiednio o 16% i 20% wyższa niż wytrzymałość na ściskanie drewna dębu modyfikowanego w tych samych temperaturach. Wytrzymałość na ściskanie wzdłuż włókien drewna dębu i tauari zależała liniowo od gęstości drewna i obciążenia wywieranego na próbkę.

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