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Outline on selected properties of densified veneers and the produced plywood

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Abstract. Wood densification is one of the methods used to modify its properties to create a material with an increased density and implicitly improved properties. Generally, densification is applied to low-density and fast-growing wood species. Lower pressures and temperatures are applied for shorter time spans to densify veneers when compared to solid wood. Along with their increased strength, hardness, and durability, densified veneers present an attractive dark colour, a smooth surface, improved gloss, and higher thermal conductivity. There is a special interest in densified veneers for plywood production. These products present increased dimensional stability, higher strength properties, and a pleasant appearance having various applications. The present paper revises selected properties of densified veneers made of black alder wood species and the mechanical properties of plywood when produced from them.

1. Introduction

The main objective of wood densification is to achieve a value-added material having increased density and implicitly improved properties, such as strength, hardness, abrasion resistance, and durability, apart from its aesthetic and commercial value [1]. The densification process is a thermal compression in a hot press that can be performed under two systems, open-system or closed-system. In the first case heat and pressure with no controlled humidity conditions are used (thermo-mechanical densification) while in the second case, there is a controlled environment and heat, steam, and pressure are applied (thermo-hydro-mechanical densification). The densification process of wood can take place in either a longitudinal or transverse direction (in radial or tangential direction) of a wood sample. The densification of wood may refer to the compression of the whole thickness of a wooden sample (bulk densification) or only the cells close to the surface layer (surface densification). It was shown that the surface densification process can decrease the time required for the compression stage and other additional treatments to eliminate the set-recovery and reduce the production and energy costs [2]. As a result of densification, there is a shape-memory effect, also called set-recovery which is produced by the build-up and release of internal stresses in densified wood and can be a long-term process. The spring-back is an elastic recovery of deformation when the load is removed. Generally, densification is



applied to low-density and fast-growing species [3]. Production processes and material properties of densified wood have been reviewed [4]. The thermal compression applied to wood and the effects on wood properties have been previously studied [5-7]. Hardness and bending properties have been extensively evaluated. It was shown that the shear strength in the grain direction could be increased more than ten times when a thermo-hydro-mechanical densification was applied [5]. The results obtained by Kutnar et al. [8] confirmed the findings of Kamke [6], that the increase in bending properties is almost equal to the increase in density through wood densification. Rautkari et al. [7] reported a two-times increase in hardness after densification applied to Scots pine wood samples of different thicknesses. Using the same method and a hydrothermal post-treatment on spruce, the study performed by Kariz et al. [9] resulted in a slight increase in hardness but almost the same increase in bending as for the surface layer density. The structure and properties of densified veneers under both systems have already been studied [10-16] along with other additional treatments applied, such as drying or oil-heat treatment [13]. Regarding thermo-mechanical densification, Bekhta [14] developed a patent for producing plywood made of veneers densified in an open-system. Plywood and other laminates are substitutes for solid wood in various applications. These composites can be produced using densified veneers [1, 12, 15]. These products present increased dimensional stability, higher strength properties, and improved durability. They can have large sizes and present a pleasant appearance. There is a drawback caused by the glue amount during their production. A decreased adhesive rate is enough to obtain such composites from densified veneers [10, 16]. Lower pressures and temperatures are applied for shorter time spans to densify veneers compared to solid wood [14]. Along with their increased strength, hardness, and durability, densified veneers present some other enhanced properties, such as an attractive dark colour, a smooth surface, improved gloss, and higher thermal conductivity [17-19].

Black alder is a fast-growing species with low density, good workability and properties, and a pleasant appearance. It is known for its traditional uses, such as spinning wheels, kitchen utensils, decorative cigar boxes, clogs, and musical instruments, and specific industrial uses, such as furniture, saunas, cladding, veneers, and plywood production.

Selected properties of densified veneers made of black alder are to be discussed in this work, such as the thickness change, mass loss, density, compression ratio, wood structure, surface quality, gloss, and colour, along with the mechanical properties of plywood when produced from them [15-19].

2. Effects of densification on the properties of black alder veneers

2.1. Densification of the veneer samples

Veneer samples of black alder cut by rotary-peeling process under industrial conditions, having a thickness of 1.5 mm and dimensions of 140 mm by 100 mm with a low moisture content of about 5%, have been prepared for densification. To increase the properties and achieve value-added plywood the veneer sheets were subjected to thermo-mechanical densification (open-system) applied for 4 min under a temperature of 150°C, and pressure levels between 4 - 12 MPa.

A laboratory hot press was employed for densification. The temperature of 150°C for veneer densification was found enough to provide the best values for the bending and bonding properties of the plywood panels [16]. After densification, the veneer samples were cooled down to room temperature. Before any other test, they were kept under constant conditions (20°C and RH 65%).

2.2. Property change: thickness, mass, density, compression ratio

After densification, the veneer suffers changes in thickness, mass, and density. Table 1 presents the definitions, equations (1 to 4), and property changes after the densification of black alder veneers. The higher the densification pressure was applied, the higher the property change was achieved. It was also found that the veneer mass loss was less affected by the densification pressure because the process temperature was not very high [20]. The vaporization of extractives occurs at temperatures higher than 150°C, but there might be also low organic volatiles evaporating at lower temperatures [21].

The thermal loss of water and minor chemical changes during densification can explain these values. The density increased with the densification temperature and pressure because wood becomes softer under heating and the void volume of the lumens is reduced causing a higher number of cell walls per unit volume [4, 7]. As expected, the density of densified veneers increased with the rising compression ratio values. Thus, the density of alder veneers when densified at 150°C and 12 MPa was found to reach 864 kg/m³. Bekhta et al. [15] determined a density change after densification higher than 100% for alder and over 50% for birch in the case of veneers densified at 200°C and 12 MPa.

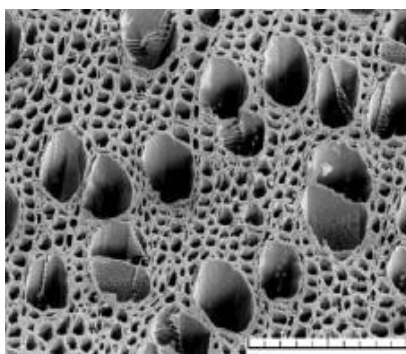
Table 1. Changes of black alder veneer after densification [15]

Property	Equation	No.	Description	Ranging interval* for pressure from 4 to 12 MPa
Thickness change (TC), %	$TC = \frac{TA - TB}{TB}$	(1)	TA/B are thicknesses after and before densification	-14.9 to -47.5
Mass loss (ML), %	$ML = \frac{m0 - m1}{m0}$	(2)	m0/I are mass before and after densification	3.5 to 4.2
Density change (DC), %	$DC = \frac{DA - DB}{DB}$	(3)	DA/B are density after and before densification	15 to 84
Compression ratio (CR), %	$CR = \frac{TB - TA}{TB}$	(4)	TA/B are thicknesses after and before densification	14.9 to 47.5

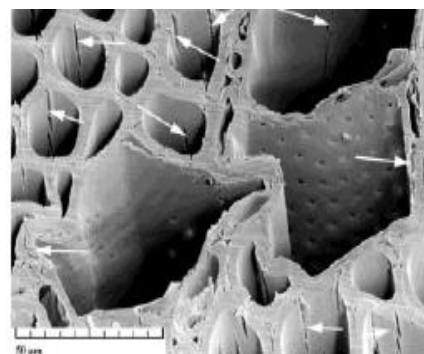
Note: Initial wood density 468 kg/m³, Density increases from 539 to 864 kg/m³, *selected intervals [15]

2.3. Changes in the anatomical structure of the veneer samples

The anatomical structure of veneers before and after densification was evaluated with the help of a high-vacuum Scanning Electron Microscopy (SEM) system (figure1). Numerous cracks are produced in the cell walls when high temperatures and pressures are applied for veneer densification. Possible reasons can be low moisture content or brittleness, lower strength, strains before densification, and cracks formed during peeling and drying. White arrows indicate the cracks in the cell walls of the libriform fibers.



a- Size of vessels (85.97 μm)



b- Size of vessels (51.71 μm)

Figure 1. SEM images of control (a) and densified black alder veneer at 150°C and 8 MPa (b) [15]

2.4. Changes in the surface quality of the veneer samples

The surface quality of a veneer is evaluated by its surface roughness which is a result of wood morphology including cell structure, early and latewood, density, grain, knots, and the cutting method of veneer, along with other factors related to harvesting, treatments, and cutting. The surface quality of veneers influences further manufacturing processes, affecting the bonding and coating properties. It was found that the plywood made of densified veneers by using a lower adhesive rate presented higher shear

strength [10, 11] and the coating performance was improved [22]. The Zeiss ME-10 stylus profilometer was employed for roughness measurements [17]. The temperature and pressure applied for densification influence the veneer surface roughness [11]. The veneer microstructure is influenced by the pressure, an increase in density is produced while a strong effect in roughness is generated by the temperature [17]. A considerable decrease in all roughness parameters (ISO 4287) as a function of the pressure level applied for densification was noticed (table 2).

Table 2. Variation of roughness parameters as a function of black alder veneer densification [17]

Veneer type and pressure interval for densified veneers	Roughness parameter [17]				
	R _a , μm (arithmetic average height)	R _z , μm (average peak to valley)	R _q , μm (root mean square)	R _p , μm (maximum peak height)	R _v , μm (maximum valley depth)
control	5.12	25.22	6.31	12.75	12.47
Densified/ 4 to 12 MPa	1.10 - 0.80	6.26-4.45	1.41-1.00	2.90-2.34	3.36-2.12

2.5. Changes in the gloss of the veneer samples

The gloss is the consequence of the ability of wood to reflect light. It depends on the wood structure, the degree of smoothness and the section type on which the light falls, the wood health condition and wood moisture content, and the light incidence angle. The gloss increases the aesthetic aspect of wood and consequently its use value. A PICO GLOSS 503 device was employed to measure the gloss of the veneer samples at 20°, 60°, and 85° geometry, along and across the grain (ISO 2813).

Complete specular light reflection, which is perfect gloss, would be 100 % and complete diffuse light reflection matt would be 0 % [18]. The results of the gloss measurement performed on control and densified veneers are compiled in table 3. The gloss presents different values for the two measurement directions, explained by the anatomical structure and irregularities on the veneer surface.

Densified veneers present higher gloss values when the pressure for densification is increased. The reason comes from a smaller light scattering of smoother veneers [18]. The densification was found to improve the attractiveness of the veneer surface and allow its characteristics to remain visible so that such results can have practical applications in organic coatings to achieve value-added surfaces for furniture.

Table 3. Gloss values of control and densified black alder veneers after densification [18]

Pressure level, MPa	Gloss across the grain at geometry			Gloss along the grain at geometry		
	20°	60°	85°	20°	60°	85°
	control	1.1	2.9	1.1	1.2	4.2
4 to 12	1.1-1.3	4.5-5.4	7.3-8.2	1.2-1.4	6.4-7.5	16.9-18.1

2.6. Changes in the colour of the veneer samples

The colour of wood varies from one species to another and such differences are due to the chemical composition of wood, growth conditions, felling season, storage, drying, exposure to light, heat, moisture, and weathering. The densification process applied to veneers affects their surfaces, particularly their colour. When subjected to densification, less decorative species can get colour and texture similar to exotic species. To measure the colour of veneer a Chroma Meter device was employed (ISO 7724-2) and the CIELab system was applied [19]. The colour coordinates of the control and densified black alder veneers are displayed in table 4 and the colour changes before and after densification are presented in figure 2 [19].

There is little change in lightness regardless of the pressure level. These changes are reinforced by the combination of higher densification temperature and pressure levels [19]. Black alder veneer showed a tendency to become greener during the densification process. The redness hue of wood is correlated with the extractive content [19]. The yellowness is governed by the photochemistry of wood components, lignin especially, and its derivatives, such as quinones and stilbenes [19]. The results of these studies can be applied on an industrial basis and used to configure a new colour approach to this wood species.

Table 4. Colour coordinates of control and densified black alder veneers [19]

Pressure level, MPa	Colour coordinates		
	L* (degree of lightness)	a* (degree of redness and greenness)	b* (degree of yellowness and blueness)
control	75.58	7.48	31.08
4/8/12	74.06/77.43/71.68	7.27/5.51/8.10	26.84/21.62/25.10



Figure 2. Colour changes of black alder veneers before and after densification [19]

3. Plywood made of densified and non-densified black alder veneers

The combination of heat and compression applied to veneers enhanced the plywood properties and the glue line strength. Previous research studies showed interest in plywood produced from densified veneers with decreased adhesive amount and lower pressure applied [11, 23, 24]. The thermo-mechanical densification was applied to veneers of different thicknesses to produce plywood with various lay-up structures [23]. A new lay-up structure of veneers with alternate layers with densified and non-densified veneers within the same plywood structure (densified outer layers) was applied to generate value-added wood-based products [16]. Selected properties of the plywood made of black alder veneers (with and without densification or mixed) are evaluated in this section, such as the compression ratio and density, modulus of rupture, modulus of elasticity, and shear strength.

3.1. Manufacturing of the plywood samples

Commercially veneers of black alder of 1.5 mm thickness were used for this study. The veneers were densified under laboratory conditions at a constant schedule. Five-ply plywood samples have been produced using the same equipment. Three different plywood types were manufactured as presented in table 5. The adhesive producer recommends 110 to 150 g/m² glue spread for plywood manufacturing. In this case, the adhesive ratios were reduced by almost 50% of the recommended value [16]. A commercial urea-formaldehyde resin was used to manufacture the plywood.

Table 5. The pressing schedule for plywood manufacturing [16]

Densification schedule	Veneer type	Plywood type	Glue Spread, g/m ²	Plywood pressing schedule
0	Control	Non-densified	80	
T=150° C P=2 MPa t= 3min	Densified	Densified	60	T=130° C P=1.8 MPa t=270+60 s
		Mixed	70	

3.2. Properties of the plywood samples

The properties of the plywood samples were determined according to specific standards using laboratory equipment [16]. The values of plywood thickness for all types of panels were lower than the standardized ones for thin veneers [16]. The values for all properties are displayed as a function of plywood type in table 6.

Table 6. Properties of the plywood samples made of black alder veneers [16]

Standard	Property	Plywood type		
		Non-densified	Densified	Mixed
EN 315	Thickness, mm	6.98	6.84	6.80
	Compression ratio*, %	11.1	5.0	8.8
EN 323	Density, kg/m ³	607.4	608.9	607.1
	Modulus of Rupture, MPa	84.21	102.18	96.44
EN 310	Modulus of Elasticity, MPa	9034	9644	8553
EN 314	Shear Strength, MPa	2.98	2.67	2.89

Note: * $CR_p = (T_v - T_p)/T_v \times 100$ (%), in which T_v is the total thickness of all veneers (mm) and T_p is the thickness of the panel (5)

While the overall density of the plywood panels slowly increased, the bending properties were enhanced due to the increased strength and stiffness of the densified veneers. Similar trends were found in previous studies for beech plywood [23]. A little difference in densities and bending properties has been noticed for plywood made from densified and mixed veneer types. A satisfactory bonding for indoor applications was achieved for all plywood panels, above the standardized limit of 1 MPa [16]. The final products meet the standard requirements for plywood panels [16]. Therefore, added-value plywood products can be obtained in the veneer-based industry with a proper lay-up structure [1, 16].

4. Conclusions

Selected properties of densified veneers made of black alder and the mechanical properties of the plywood samples made of them have been evaluated in this study. The higher the densification pressure applied to veneers, the higher the property change was achieved. Low glue consumption compared to industrial conditions has been used for plywood manufacturing. The densification produced the best results for the bending and bonding properties of the plywood. Due to their good surface quality, the densified veneers do not need sanding and their attractive colour allows transparent varnish. These plywood products produce no dust, present low emissions of toxic compounds, have a low cost, and can have brief applications.

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