
Effects of Thermo-Mechanical Densification Applied to Veneers of Fast-Growing Species to Produce Value-Added Plywood Panels

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ABSTRACT

Plywood and other laminated panels are used as substitutes for solid wood in various applications. There is a special interest for the densified wood veneers to produce such composites. In this chapter selected properties of densified veneers made of two fast-growing species are presented along with a new lay-up veneer structure of plywood to produce value-added panels for indoor applications. Based on the findings of this study the densification process enhanced the veneer surface quality and gloss, giving also a pleasant darker colour to the veneers and the plywood made of them. The new plywood structure with alternate layers of densified and non-densified veneers was proved to be an efficient solution to obtain panels with improved properties.

Keywords: Black alder; birch; plywood; properties; densification.

1. CONSIDERATIONS ON DENSIFICATION OF WOOD AND VENEERS

Wood densification is one of the methods used to modify wood in order to enhance its properties. The main objective of wood densification is to achieve a value-added material having an increased density and implicitly improved properties, such as strength, hardness, abrasion resistance and durability, apart from its aesthetic and commercial value. The densification process is a thermal compression in a hot press and it can be carried out either in an open-system using heat and pressure without any control of the environmental humidity (it is called thermo-mechanical densification-TM) or in a closed-system using heat, steam and pressure under controlled environmental conditions (it is called thermo-hydro-mechanical densification-THM). The densification process of wood can take place in either longitudinal or transverse direction of a wood sample. As regards transverse direction, the densification can be applied in radial or tangential direction. However, densification in the radial direction has been extensively used during the past decades [1]. 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. A method to select the most suitable wood species for surface densification was recently developed giving confirmation of the results from other previous studies on Scots pine, spruce and poplar [3].

The thermal compression applied to wood and the effects on wood properties have been previously studied [4-11]. Hardness and bending properties have been extensively evaluated. It was shown that

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the shear strength in the grain direction could be increased more than ten times when a THM treatment was applied [5]. The results obtained by Kutnar et al. [12] 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. [10] 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. [13] resulted in a low increase in hardness but almost the same increase in bending as for the surface layer density.

The specialty literature provides some information about the structure and properties of wood veneers densified for a short time in both open and closed-systems [14-24]. Combinations with other treatments such as drying or oil-heat treatment have been also performed [21]. As regards TM densification, Bekhta [22] developed a patent on the production of plywood made of veneers densified in an open-system. Plywood and other laminates are substitutes of solid wood in various applications.

Nowadays, there is a special interest for densified wood veneer to produce such composites [18, 23]. These products present increased dimensional stability and higher strength properties. They can have large sizes and along with some biological benefits, they have a pleasant appearance. Apart of these advantages they have a drawback caused by the adhesive amount for their manufacturing. But when using densified veneers a lower adhesive rate can be applied [14, 24]. A densified veneer can be achieved under lower pressures and temperatures for shorter time than those required for solid wood [22]. Along their increased strength, hardness and durability, densified veneers present some other enhanced properties, such as an attractive dark colour, a smooth surface, improved gloss, wettability and higher thermal conductivity [25-28].

Selected properties of densified veneers made of two fast-growing species, such as black alder and birch, are to be discussed next: thickness change, mass loss, density, compression ratio, wood structure, surface quality, gloss and colour.

2. EFFECTS OF TM DENSIFICATION APPLIED TO VENEERS OF BLACK ALDER AND BIRCH

Black alder (*Alnus glutinosa* Gaertn.) and birch (*Betula verrucosa* Ehrh.) are fast-growing species with a pleasant light colour appearance (Fig. 1), having almost similar workability properties. Solid wood of these species is mostly used for joinery, small furniture and saunas. Apart of their use for furniture manufacturing, the veneer of these species are used for veneer-based composites as well [23, 29]. To increase their properties and achieve value-added plywood and laminates, such veneer sheets are here subjected to TM densification with the help of heat and pressure applied for a short period of time (open-system). A selected list of articles published on the subject and species was prepared and will be used to better describe the experiment itself and to highlight the properties of veneers after densification [23, 26-28].

2.1 Densification Process of Veneers

Veneer samples of black alder and birch cut by rotary-peeling process under industrial conditions, having a thickness of 1.5 mm and dimensions of 140 mm by 100 mm, have been prepared for the TM densification. They had a low moisture content of about 5%. For such an approach, a laboratory hot press was employed, as it is presented in Fig. 2. The densification schedule was set for: a temperature of 150°C, three pressure levels from 4 to 12 MPa and 4 min time span. This temperature was selected because in a previous study the temperature of 150°C for veneer densification was found enough to provide the best values for bending and bonding properties of plywood panels [24]. After densification the veneer samples were cooled down to room temperature, then and before any other test, the samples were kept under constant conditions at the temperature of 20°C and a relative air-humidity of 65%, until they had constant mass weight.

2.2 Some Changes after Densification

There are several changes that appeared after veneer densification, such as thickness change (TC), mass loss (ML) and density change (DC). Compression ratio (CR) is an important parameter and it

represents the degree of change in thickness to the original one. To obtain these parameters the dimensions and mass of veneer samples were measured before and after densification. Table 1 displays the equations used to determine these changes and Table 2 shows their trend and the variation interval as a function of wood species and densification pressure.



a



b

Fig. 1. Surface of black alder (a) and birch (b)

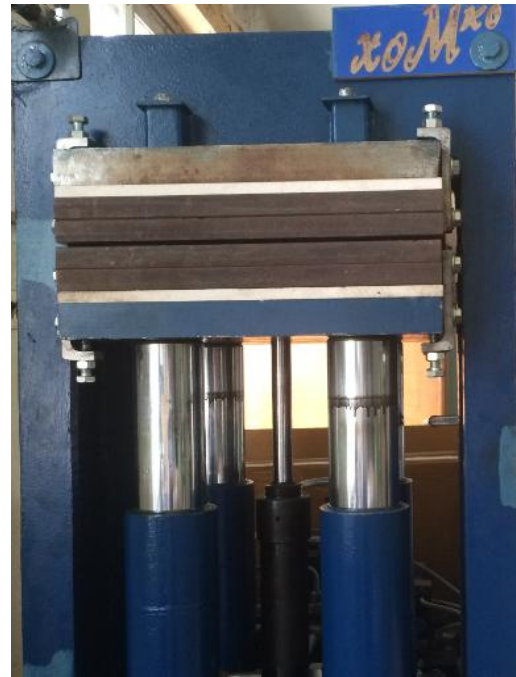


Fig. 2. Laboratory press

Table 1. Definitions of properties changed after densification

| Eq.No. | Changed property | Equation | Description |
|--------|---------------------------|---------------------------|--|
| 1. | Thickness change (TC), % | $TC = \frac{TA - TB}{TB}$ | TA and TB are thicknesses after and before densification |
| 2. | Mass loss (ML), % | $ML = \frac{m0 - m1}{m0}$ | m0 and m1 are mass values before and after densification |
| 3. | Density change (DC), % | $DC = \frac{DA - DB}{DB}$ | DA and DB are densities after and before densification |
| 4. | Compression ratio (CR), % | $CR = \frac{TB - TA}{TB}$ | TA and TB are thicknesses after and before densification |

It appears that the changes of properties for both species under study respected the same trends. Major changes were noticed for alder when compared to birch which is supported by the species density. The higher the densification pressure was applied, the higher the property change was achieved. It was also found that the veneer ML of both species was less affected by the densification pressure because the process temperature was not very high [30]. The vaporization of extractives takes place at temperatures higher than 150°C [31]. The thermal loss of water and minor chemical changes during densification can explain the ML low values. Due to its lower density, alder was more densified than birch, the ranging intervals of DC are larger for alder when compared to birch. 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 [4,10]. As expected, the density of densified veneers was found to increase with the rising of CR values. Thus, the density of alder veneers densified at 150°C and 12 MPa was found to reach 864 kg/m³, while 838 kg/m³ was determined for birch. Bekhta et al. [23] determined a density change after densification higher than 100% for alder and over 50% for birch for veneers densified at 200°C and 12 MPa.

Table 2. Changes of veneers densified at 150°C and pressure level from 4 to 12 MPa [23]

| Wood species/ Initial density | Property change | Property ranging interval* for pressure from 4 to 12 MPa | Trend |
|--|---|---|-----------------|
| Black alder / 468 kg/m ³ | TC, % | -14.9 to -47.5 | decreasing |
| | ML, % | 3.5 to 4.2 | almost constant |
| | DC, % | 15 to 84 | increasing |
| | CR, % | 14.9 to 47.5 | increasing |
| | Alder density increases from 539 to 864 kg/m ³ | | |
| Birch / 625 kg/m ³ | TC, % | -11.3 to -28.5 | decreasing |
| | ML, % | 4.3 to 4.4 | almost constant |
| | DC, % | 6.8 to 34.1 | increasing |
| | CR, % | 11.3 to 28.5 | increasing |
| | Birch density increases from 667 to 838 kg/m ³ | | |

*selected intervals [23]

2.3 Changes in Morphology

To obtain high-resolution images of the changes in anatomical structure of veneers before and after densification, a high-vacuum SEM system (VEGA TS 5139) was employed. The samples were subjected to a gold-sputtering coating. The microstructures of both control and densified veneers are displayed as for comparison in Fig. 3.

White arrows indicate the cracks in the cell walls of the libriform fibres. Table 3 presents the size of vessels for veneers of black alder and birch densified under a constant temperature of 150°C and variable pressure from 4 to 12 MPa. Table 4 briefly highlights the effects of densification on the veneer microstructure.

Table 3. Size of vessels (µm) of veneers made of black alder and birch before and after densification at 150° C and three pressure (P) levels [23]

| Wood species | Control | P=4 MPa | P=8 MPa | P=12 MPa |
|--------------|---------|---------|---------|----------|
| | | | | |
| Black alder | 85.97 | 68.48 | 51.71 | 28.50 |
| Birch | 106.71 | 85.40 | 74.93 | 59.54 |

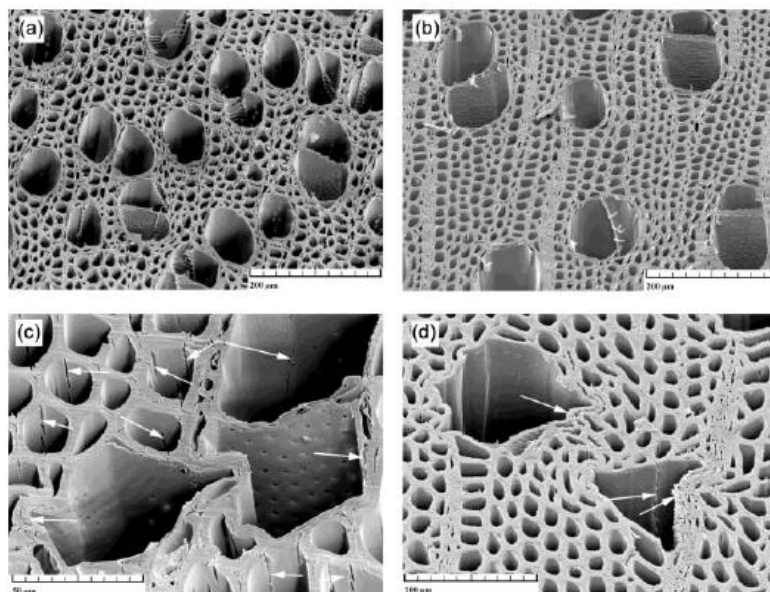


Fig. 3. SEM images of control alder (a) and birch (b) veneers and densified veneers: alder at 150°C and 8 MPa (c) and birch at 150°C and 12 MPa (d) [23]

Table 4. Effects of densification on the microstructure of veneers [5, 23]

| Process | Effects on the microstructure of veneers |
|----------------|--|
| Densification | <p>A densified veneer is much more affected when compared to solid wood after densification</p> <p>In longitudinal tangential surfaces the pores and microcracks created during peeling and drying are closed during densification</p> <p>A substantial number of cracks in the cell walls are recorded for densified veneer at high densification temperatures and pressures.</p> <p>Possible reasons:</p> <ul style="list-style-type: none"> - Low moisture content or brittleness - Lower strength - Strains before densification - Craks formed during peeling and drying <p>Densified veneers are smoother as a result of plasticization under high temperature and pressure</p> <p>The cell walls are buckled through densification, the volume of void spaces is reduced. The density increases by reducing the void volume.</p> <p>When the pressure increases, the vessels are subjected to deformation, their size decreases (Table 3) and they collapse. Cell collapse influences the physical-mechanical properties of densified material.</p> <p>The compression ratio has a major effect on the size of vessels and tends to be inversely proportional to their size</p> |

2.4 Changes in Surface Quality of the Veneer Samples

The surface quality of a veneer is evaluated by its surface roughness that is a result of wood morphology including cell structure, early and latewood, density, grain, knots and the cutting method of veneer. Other factors may be added here, such as the season of log harvesting, heating or steaming of log, cutting conditions and drying parameters [32]. The final veneer-based product is influenced by the veneer characteristics. The surface quality of veneers influences further manufacturing processes, affecting the bonding and coating properties, especially. Densification is an effective method to improve the veneer roughness. It was found that by using densified veneers having smooth surfaces for plywood manufacturing, a higher shear strength at a lower glue spread is achieved [14,16]. Moreover, the coating performance was enhanced when smoother surfaces are used for veneer-based composites [33-35]. To measure the surface roughness a stylus profilometer of Zeiss ME-10 type was used. Table 5 presents a selection of roughness parameters under evaluation. Examples of roughness profiles are shown in Fig. 4.

Table 5. Roughness parameters [36]

| | Roughness parameter | Definition |
|----------------------|----------------------------------|---|
| R_a | arithmetic average height | arithmetic mean of absolute departures of the roughness profile from the mean line. |
| R_z | average peak to valley roughness | maximum peak to valley height of the profile within sampling length |
| R_q | root mean square | is the square root of the arithmetic mean of squares of original values |
| R_p | maximum peak height | maximum height of the profile above the mean line within sampling length |
| R_v | maximum valley depth | maximum depth of the profile below the mean line within sampling length |

The surface roughness of veneer depends on the densification temperature and pressure [16]. The pressure strongly affects the veneer microstructure, resulting in density increase while the temperature produces a strong effect on surface roughness. Therefore, to achieve a desired surface quality, a higher temperature for densification is required. The effect of densification temperature on the roughness profile recorded for control and densified veneers at high temperature level (200°C) is seen in Fig. 4 [26]. To get a better overview on the changes in surface quality after veneer densification, the variation of roughness parameters as a function of different pressure levels applied for densification at a constant temperature of 150°C is presented in Table 6 for both species under study. Roughness values of control alder veneer are higher than those of birch while after densification they range within almost similar intervals for both species.

A considerable decrease in all roughness parameters as a function of pressure level applied for densification was noticed.

2.5 Changes in Gloss of the Veneer Samples

The gloss is the consequence of the ability of wood to reflect light. It depends on the wood structure, on the degree of smoothness and the section type on which the light falls, on the health condition and wood moisture content and on the light incidence angle. The gloss definitely 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° angles of incident light, along and across the grain. Complete specular light reflection, which is perfect gloss, would be 100 %, and complete diffuse light reflection matt would be 0% [27]. The results of the gloss measurement performed on control and densified veneers at 150° and three pressure levels are compiled in Table 7.

It was noticed that gloss presented different values for the two directions of measurement. Such result is explained by the anatomical structure and irregularities on the veneer surface. Overall, when compared to control samples, densified veneers have increased gloss values with increasing the

densification pressure. The reason comes from a smaller light scattering of smoother veneers. In his study, Bekhta et al. [27] concluded that the veneer gloss increased with the increase of densification temperature from 100°C to 200°C and pressure from 4 MPa to 12 MPa. Densified birch veneers have higher gloss than densified alder. The gloss of veneers is higher after their densification for both wood species under study. The densification was found to improve the attractiveness of veneer surface and allows its characteristics to remain visible so that such results can have practical applications in organic coatings to achieve value-added surfaces for furniture.

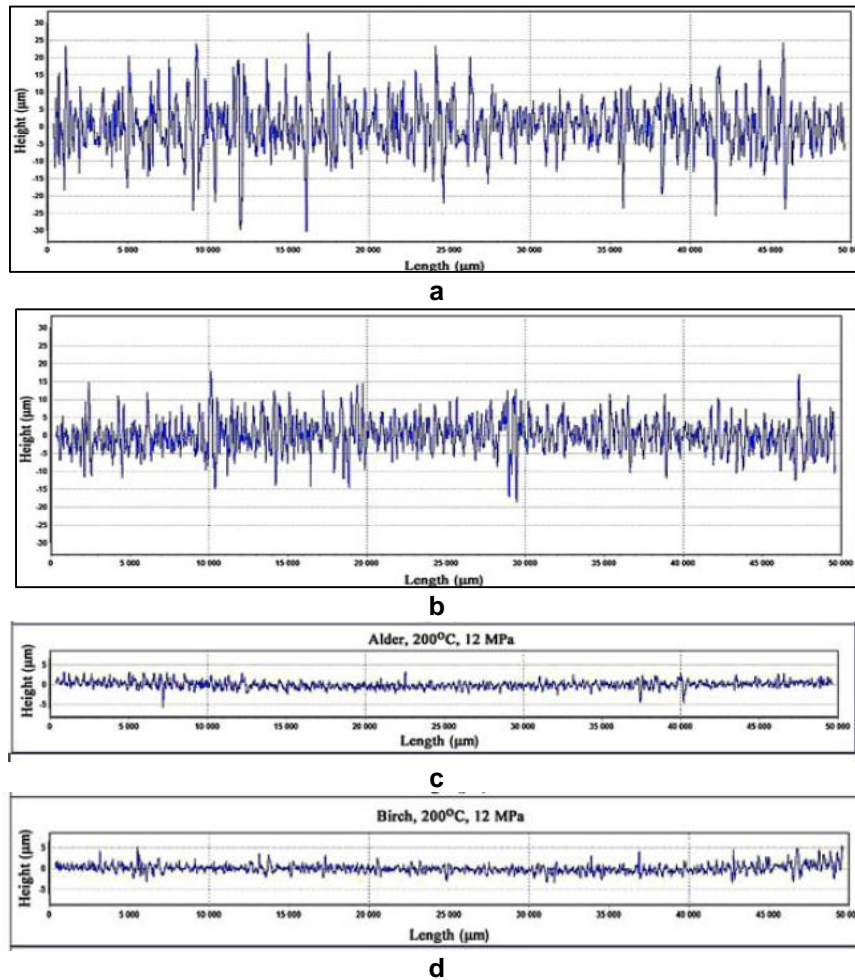


Fig. 4. Typical roughness profiles before and after densification for alder (a, c) and birch (b, d) [26]

Table 6. Variation of roughness parameters as a function of veneer densification temperature of 150°C and pressure levels from 4 to 12 MPa [26]

| Wood species | Veneer type and pressure interval for densified veneers | R _a , µm | R _z , µm | R _q , µm | R _p , µm | R _v , µm |
|--------------|---|---------------------|---------------------|---------------------|---------------------|---------------------|
| Black alder | control | 5.12 | 25.22 | 6.31 | 12.75 | 12.47 |
| | 4 to12 MPa | 1.10 - 0.80 | 6.26-4.45 | 1.41-1.00 | 2.90-2.34 | 3.36-2.12 |
| Birch | control | 3.44 | 17.15 | 4.21 | 8.80 | 8.34 |
| | 4 to12 MPa | 1.27-0.81 | 6.68-4.69 | 1.62-1.04 | 3.12-2.26 | 3.55-2.43 |

Table 7. Gloss values of control and densified veneers after densification at 150° and three pressure levels [27]

| Wood species | Pressure level, MPa | Gloss across the grain | | | Gloss along the grain | | |
|--------------|---------------------|------------------------|-----|------|-----------------------|------|------|
| | | angle of incidence | | | angle of incidence | | |
| | | 20 | 60 | 85 | 20 | 60 | 85 |
| Black alder | control | 1.1 | 2.9 | 1.1 | 1.2 | 4.2 | 1.3 |
| | 4 | 1.1 | 4.5 | 7.3 | 1.2 | 6.4 | 16.9 |
| | 8 | 1.3 | 5.5 | 10.8 | 1.4 | 7.9 | 18.1 |
| | 12 | 1.3 | 5.4 | 8.2 | 1.4 | 7.5 | 16.4 |
| Birch | control | 0.9 | 2.5 | 0.8 | 1.0 | 3.7 | 1.2 |
| | 4 | 1.3 | 4.5 | 7.8 | 1.5 | 7.0 | 12.7 |
| | 8 | 1.6 | 6.3 | 13.9 | 1.7 | 9.1 | 20.4 |
| | 12 | 1.7 | 6.8 | 17.2 | 1.9 | 10.2 | 25.7 |



PICO GLOSS 503

2.6 Changes in 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, weathering. The densification process applied to veneers affects their surfaces, particularly their colour. When subjected to densification (heat and pressure) less decorative species can get a colour and texture similar to exotic species. To measure the colour of veneer a Chroma Meter device is employed. The CIELab system is used for colour evaluation [37]. L^* , a^* and b^* colour coordinates are determined both for control veneers and densified veneers. Hereinafter, the colour differences (ΔL^* , Δa^* and Δb^*) and then the total colour change ΔE^* are calculated based on the equations presented in Table 8. The colour coordinates of control and densified veneers after densification at 150° and pressures of 4, 8 and 12 MPa are displayed in Table 9.

Table 8. CIELab system equations [37]

| Eq. No | Equations | Description |
|--------|--|---|
| 5. | $\Delta L^* = L_d^* - L_c^*$ | L^* is the degree of lightness; a^* – degree of redness and greenness; b^* – degree of yellowness and blueness, and the subscripts d and c indicate the values for the densified samples and control references, respectively |
| 6. | $\Delta a^* = a_d^* - a_c^*$ | |
| 7. | $\Delta b^* = b_d^* - b_c^*$ | |
| 8. | $\Delta E^* = \sqrt{((\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2)}$ | |

Table 9. Colour coordinates of control and densified veneers after densification at 150° and three pressure levels [28]

| Wood species | Pressure level, MPa | Colour coordinates | | |
|--------------|---------------------|--------------------|-------|-------|
| | | L^* | a^* | b^* |
| Black alder | control | 75.58 | 7.48 | 31.08 |
| | 4 | 74.06 | 7.27 | 26.84 |
| | 8 | 77.43 | 5.51 | 21.62 |
| | 12 | 71.68 | 8.10 | 25.10 |
| Birch | control | 82.38 | 2.96 | 24.88 |
| | 4 | 80.36 | 3.79 | 25.35 |
| | 8 | 79.22 | 7.90 | 27.32 |
| | 12 | 79.54 | 7.65 | 27.20 |



Chroma Meter device

It is noticed that the value of L^* decreases due to the densification process for both species which means that the veneers lost lightness. At the densification temperature of 150°C there is little change in lightness regardless the pressure level. These changes are reinforced for the combination of higher densification temperature and pressure levels [28].

Birch shows tendency to become redder, while alder veneer shows tendency to become greener during the densification process.

The redness hue of wood is correlated with the extractive content. A direct relationship between the increase of a^* values for birch and decrease of those for alder is noticed [28]. The yellowness is governed by the photochemistry of wood components, lignin especially and its derivatives, such as quinones and stilbenes [38]. The b^* values of veneers decrease for alder and increase for birch with the rising of temperature. It appears that pressure has little effect when compared to temperature on the discoloration of veneers. A darker colour of densified veneers is achieved for the densification temperature of 200°C for different pressure levels [28]. To highlight this aspect for both species, the colour changes of densified veneers at two different temperatures and pressure levels are presented in Fig. 5. Results of these studies can be applied under industrial basis and used to configure a new colour approach of these two species.



Fig. 5. Colour changes of veneers before and after densification at 150°C and 200°C and pressure levels of 4, 8 and 12 MPa [28]

3. PLYWOOD MADE OF ALTERNATE LAYERS OF DENSIFIED AND NON-DENSIFIED VENEERS

The combination of heat and compression applied to veneers was found to enhance the plywood properties and the glue line strength of the final product [39]. There is a high interest to reduce the spread rate of adhesive for engineered products [39]. Densification of veneers prior to plywood manufacturing was found to give such result, along with a lower pressure [16, 40]. In previous studies, the veneers of one or two thicknesses were used in TM densification process to produce plywood mainly with non-densified or densified veneers, or with densified outer layers and non-densified core [16, 40, 41].

A new lay-up structure of veneers by using a combination of densified and non-densified veneers within the same plywood structure was applied to generate value-added wood-based products [24]. This approach is presented next.

3.1 Preparation of the Plywood Samples

Commercially veneers of black alder and birch (1.5 mm) were used for this study. The veneers (7.4 %MC) were densified under laboratory conditions (hot press in Fig. 2) at a constant schedule: temperature of 150° C, pressure of 2 MPa, for 3 min time span. The moisture content of densified veneer was of about 2.2%. Five-ply plywood samples have been produced from both wood species by

using the same laboratory press. Three different plywood types were manufactured, such as plywood made of: non-densified veneers (N), densified veneers (D) and mixed (M) as a combination of densified (d) and non-densified veneers (n) within the same structure by using alternate layers (d-n-d-n-d). Usually, in practice, under industrial conditions, the glue spread ranges from 110 to 150 g/m², as it is recommended by the adhesive producer. But in this study the adhesive ratios were reduced almost 50% of the recommended value [24]. To manufacture the plywood a commercial urea-formaldehyde (UF) resin was used. The pressing schedule for plywood manufacturing is presented in Table 10.

Table 10. The pressing schedule for plywood manufacturing [24]

| Wood species | Densification temperature, °C / plywood type | | Glue Spread, g/m ² Variable | Pressure, MPa | Temperature, °C | Press Time, s |
|--------------|--|---|---|---------------|-----------------|---------------|
| | | | | Constant | | |
| | | | | 1.8 | 130 | 270 + 60 |
| Black alder | 0 | N | 80 | | | |
| /Birch | 150 | D | 60 | | | |
| | 150 | M | 70 | | | |



Plywood samples

3.2 Properties of the Plywood Samples

The density of all types of plywood was determined according to EN 323 standard [42] and the compression ratio of the plywood panels was calculated using the equation below:

| Eq. No | Equations | Description |
|--------|---|---|
| 9. | $CR_p = (T_v - T_p) / T_v \times 100$ (%) | in which T_v is the total thickness of all veneers (mm) and T_p is the thickness of the panel |

MOR, MOE and the shear strength have been measured by employing laboratory testing machine and according to their specific standards [43-45]. For the bonding test the samples were immersed in water at $20 \pm 3^\circ\text{C}$ for 24h. Table 11 presents the density values along with the thickness and compression ratio of the plywood panels. There is a density difference between the two plywood panels of birch and alder as a result of the density difference between species. The values of plywood thickness for all types of panels were lower than the permissible values stipulated by EN 315 for thin veneers, in the range of 5.66–7.24 mm [46]. Figs. 6 and 7 display the average values of MOR and MOE for birch and black alder plywood as a function of plywood type (N, D and M).

Table 11. Thickness, compression ratio and density of the plywood samples [24]

| Densification temperature and plywood type | | 0 N | 150 D | 150 M |
|--|----------------------------|--------|----------|----------|
| Black alder | Thickness, mm | 6.98 | 6.84 | 6.80 |
| | Compression ratio, % | 11.1 | 5.0 | 8.8 |
| | Density, kg/m ³ | 607.4 | 608.9 | 607.1 |
| Birch | Thickness, mm | 7.03 | 6.96 | 7.06 |
| | Compression ratio, % | 10.4 | 3.3 | 5.4 |
| | Density, kg/m ³ | 747.0 | 807.9 | 766.8 |

The values of MOR and MOE of the plywood samples increased with the increase in density. No essential improvement in terms of bending properties was noticed for birch plywood D and M when compared to N even using a reduced adhesive spread. But for black alder plywood these values were higher for plywood D produced using low glue spread (60 g/m²) than for plywood N produced with 80 g/m². The plywood made of black alder veneers densified at 150°C resulted in increased values for MOR and MOE when compared to control panel N.

A lower increase rate for both bending properties was found for the densification temperature of about 180°C [24]. Results of this work are comparable to those found in previous studies. Similar trends were found by Bekhta et al. for beech plywood [39]. The MOR value (123.8 MPa) for 5-layers birch plywood made of densified veneers by cold-press and using PF adhesive (135 g/m²) was achieved by Bekhta et al. [15].

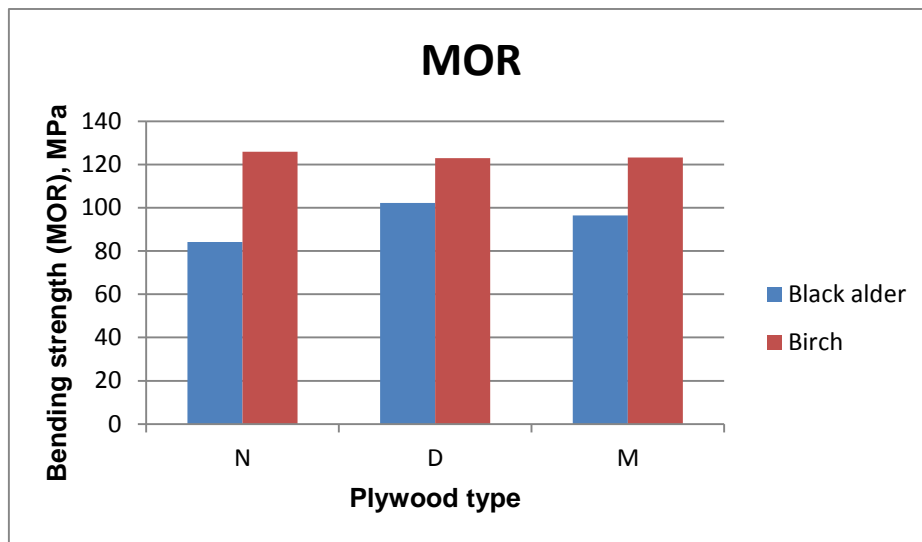


Fig. 6. Bending strength (MOR) of birch and black alder plywood as a function of plywood type [24]

Note: Densification of veneers was performed at 150° C

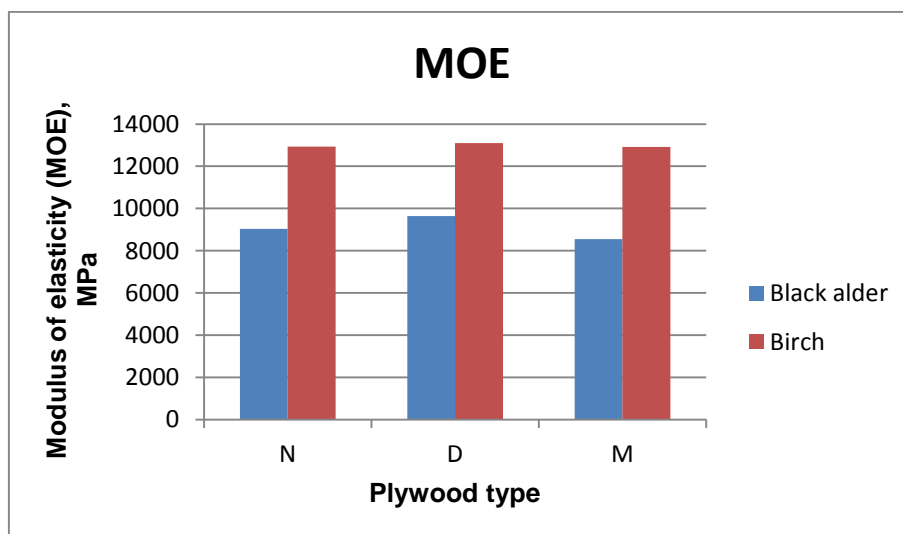


Fig. 7. Modulus of elasticity (MOE) of birch and black alder plywood as a function of plywood type [24]

Note: Densification of veneers was performed at 150° C

The results of bending properties from the extended work [24] showed that the increase of densification temperature from 150° C to 210° C resulted in a gradually decrease of bending properties for all plywood made of densified veneers (Figs. 8 and 9). The strength values are significantly affected by the density of the samples. Overall, very low differences in densities and bending properties have been noticed for plywood of D and M types.

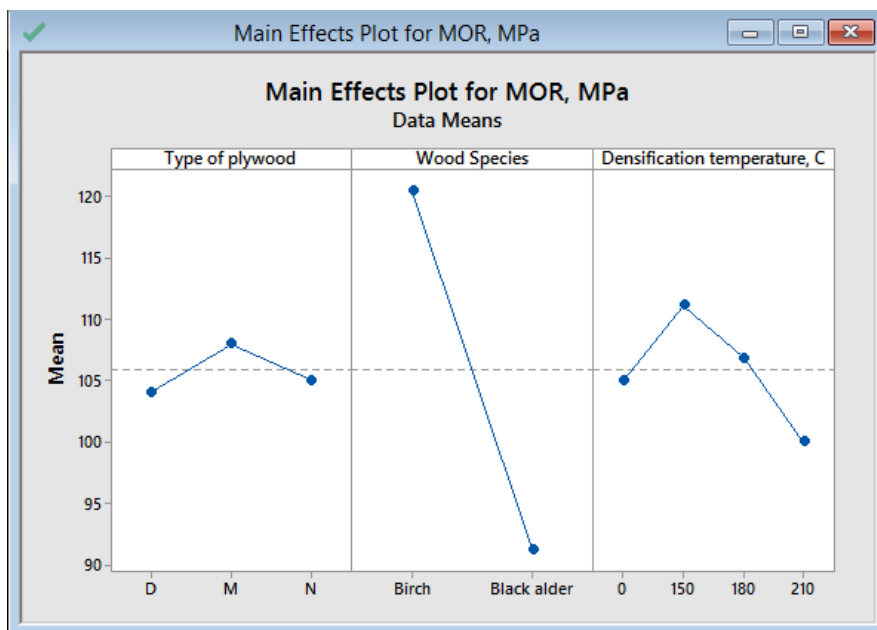


Fig. 8. Main effects plot for MOR for the plywood panels [24]

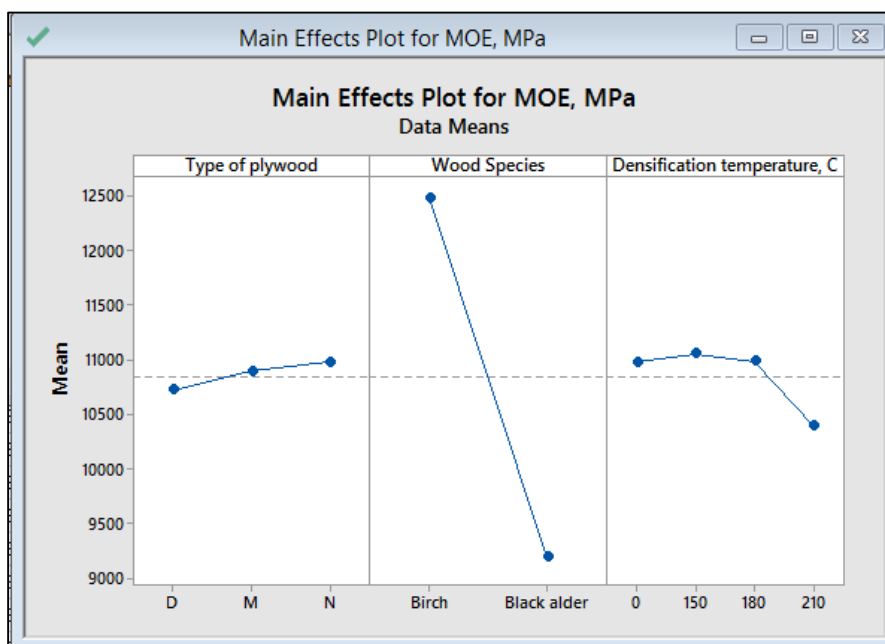


Fig. 9. Main effects plot for MOE for the plywood panels [24]

The outer densified layer is responsible for the bending strength. The values for bending properties obtained for all plywood structures were found higher than the limit values for structural plywood panels [24]. In terms of shear strength properties, a satisfactory bonding for indoor applications was

achieved for all plywood panels. They presented values above the limit of 1 MPa indicated by the EN 314-2 [45]. The results of shear strength properties are presented in Fig. 10. The main effects for bonding properties are presented in Fig. 11.

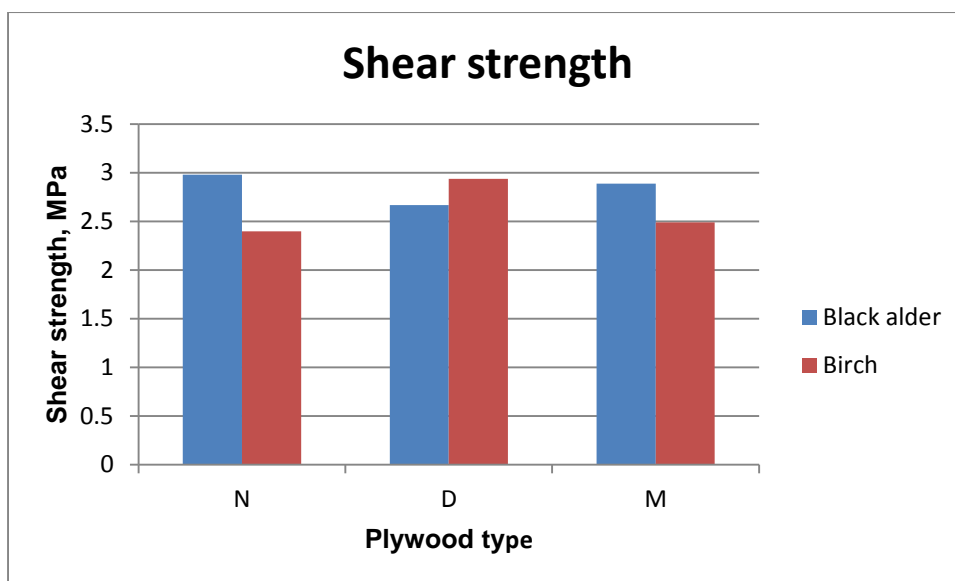


Fig. 10. Shear strength of birch and black alder plywood as a function of plywood type [24]
 Note: Densification of veneers was performed at 150° C

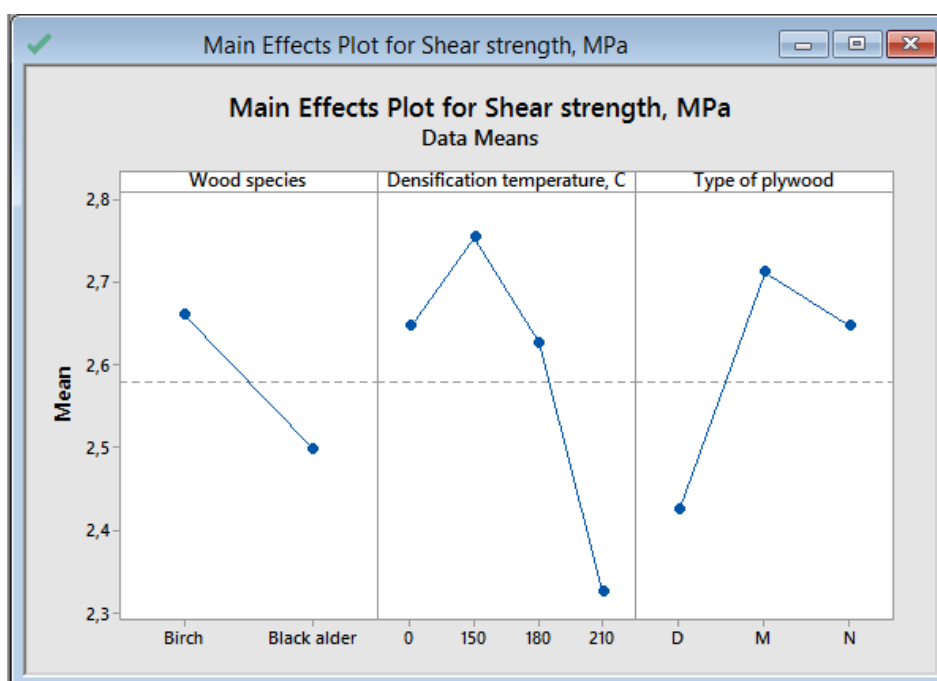


Fig. 11. Main effects plot for shear strength for the plywood panels [24]

The smoother surface of densified veneer was proved to improve the bonding of plywood [26]. Moreover, the adhesive spread should be lower for them when compared to non-densified veneers. This way the final product meets the standard requirements for plywood panels [24]. The better bonding strength for mixed structures M when compared to D type is due to the core (n-d-n) that acts like a compact adhesive layer. The glue spread of 70 g/m² gives a good bonding to the outer densified

layers. The shear strength values gradually decreased with the increase of temperature level for veneer densification [24].

4. CONCLUSIONS

Based on the results found in this work [24], it appears that the densification of veneers at 150°C provides the best results in terms of bending and bonding properties of the plywood made from densified veneers and with mixed structure by using low glue consumption. Therefore, the temperature of 150°C should be enough to densify veneers prior to plywood manufacturing. Due to their smoothness, the densified veneers do not need sanding and their attractive colour allows transparent varnish. These panels are environmentally-friendly, produce no dust, have low emissions of toxic compounds and consequently low costs for the finished product.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Any Other Remarkable Point(s): Many of his developments mentioned above as contributions are protected by 132 patents of Ukraine and Russian Federation.

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