Eur. J. Wood Prod. (2018) 76:549–562
DOI 10.1007/s00107-017-1233-4

ORIGINAL

Effect of short-term thermomechanical densification of wood veneers on the properties of birch plywood

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Received: 30 August 2016 / Published online: 16 September 2017

Abstract In this study, the physical and mechanical properties of plywood panels made from pre-compressed birch (*Betula verrucosa* Ehrh.) veneer were evaluated. Veneer sheets underwent short-term thermo-mechanical (STTM) compression at temperatures of 150 or 180 °C and at pressures of 0.5, 1.0, 1.5, 2.0, 2.5, 3.0 or 3.5 MPa for a period of 1 min prior to adhesive being applied and pressed into panels using phenol formaldehyde adhesive at 100 g/m^2 spread rate; this was one-third less than the adhesive spread used for the control panels (150 g/m^2). The pressing pressure was 1.0 MPa, which was almost half of the pressure used for the control panels (1.8 MPa); and pressing time was 3 min, also half of the pressing time used for the control panels (6 min). The results showed that surface roughness of compressed veneer, water absorption and thickness swelling of plywood panels made from compressed veneer were significantly improved. The shear strength values of plywood panels made from compressed birch veneer even with reduced adhesive spread were higher than those of plywood panels made from uncompressed veneer. The findings in this study indicated that compression of birch veneer could be considered as an alternative to produce more eco-friendly (owing to smaller adhesive spread) value-added material with enhanced properties.

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1 Introduction

Veneer-based products, such as plywood and laminated veneer lumber (LVL), have been developed and used as alternatives to solid wood products. They have various advantages in comparison with conventional solid wood, such as increased dimensional stability, uniformity and higher mechanical strength, reduced processing cost, availability in larger sizes, better appearance, and biological benefits; these products are biodegradable (whereas steel and concrete are not) (Tenorio et al. 2011). On the other hand, one of the main disadvantages of these products is using a large amount of adhesive during its manufacturing, which can be up to 20% of its total mass (de Melo and Menezzi 2014). This disadvantage decreases the veneer-based products ecological balance and makes its less favorable than solid wood, especially when considering resins derived from petrochemical resources.

Nowydays, the thermal compression process has been used to improve the properties of wood and wood materials for their wider applications. For example, densified wood veneers can potentially be used in various products for building construction, furniture, flooring, and other numerous applications (Bekhta et al. 2009; Candan et al. 2010; Diouf et al. 2011). In addition to the benefits to wood properties such as strength, surface hardness and durability (Buyuksari et al. 2012; Buyuksari 2013), the surface quality and in particular aesthetic properties, could also be improved; the color of wood becomes more attractive (Diouf et al. 2011; Bekhta et al. 2014a), the surface roughness decreases (Candan et al. 2010; Arruda and Del Menezzi 2013; Bekhta et al. 2014b); and the surface becomes glossier and smoother (Bekhta et al. 2014b, c) while minimizing the need for sanding. This improved attractiveness of the veneer surface facilitates the application of transparent organic coatings that allow

improved natural characteristics of wood to remain visible, and so the demand for them has been increasing. However, one of the main disadvantages of compressed wood is the dimensional instability and almost total deformation recovery (also known as set-recovery) when densified wood products are exposed to cycle weathering (Burmester 1973; Welzbacher et al. 2008; Laine et al. 2013).

Densified veneer also provides higher thermal conductivity and lower adhesive consumption in the manufacture of plywood compared with non-densified veneer (Asako et al. 2002; Bekhta and Marutzky 2007; Bekhta et al. 2009, 2012). In previous studies, the possibility of reducing the use of adhesives in the manufacture of plywood was investigated by using densified veneer in hot press (Bekhta and Marutzky 2007; Bekhta et al. 2012) or cold rolling process (Bekhta et al. 2009). They showed that pre-compression of veneer sheets makes it possible to produce plywood with satisfactory strength properties with lower adhesive consumption and press pressure. This was explained by the significant improvement of surface roughness. Similar work (Buyuksari et al. 2012; Buyuksari 2013) evaluated the physical and mechanical properties of MDF panels laminated with compressed veneer. These studies showed that press pressure and temperature can be used to improve the surface and bending characteristics of laminated MDF panels. All of the compressed veneer laminated panels had lower roughness and higher modulus of elasticity, modulus of rupture and hardness values compared to non-compressed veneer laminated panel.

From an anatomical point of view, veneer can be considered as an analogue to solid wood. However, with respect to thickness, the compression of veneer, for a particular degree of densification, can be achieved within less time and at lower pressures and temperatures than that required for solid wood. However, in previous studies (Bekhta and Marutzky 2007; Bekhta et al. 2009, 2012) the pressure values used for the compression process were quite high (which is typical for compression processes used for solid wood), which leads to a significant densification of wood veneer and can reduce the thickness of plywood, and, consequently, the overrun of wood raw material.

Veneer can be used not only in the production of plywood or LVL, but also for laminating particleboard and medium density fiberboard for the furniture industry (Buyuksari et al. 2012; Buyuksari 2013). Therefore, veneer roughness not only affects the spread of adhesive but also the consumption of coatings (paints, varnish) and properties of the overlaid products. Studies show that smooth surfaces need relatively little paint since the coverage and paint performance is improved (Richter et al. 1995). It is known that the bonding strength between the overlay veneer and the substrate decreases with increasing veneer roughness (Faust and Rice 1986).

In this manner, compressed veneer sheets with a smoother surface can be used successfully for plywood and LVL manufacturing as well as for the lamination of wood-based panels. Moreover, less time is needed for improving the properties of veneer compared to solid wood. In addition, dimensional stability remains a serious problem for the densified solid wood (Welzbacher et al. 2008), though it is not so important for densified veneer. The dimensional stability of final products (plywood, LVL) from veneer is usually determined by the adhesives used for their manufacturing. Therefore, there is considerable interest in finding ways to use densified veneer for manufacturing of plywood or LVL at industrial scale, but more information is needed about the changes in the physical and mechanical properties of densified veneers and panels made from them.

Therefore, the objective of this work was to evaluate the effect of the pre-compression conditions on the physical and mechanical properties of short-term thermo-mechanical (STTM) compressed veneer and plywood made with STTM treated veneer.

2 Materials and methods

2.1 Wood veneer samples

Rotary-peeled birch (*Betula verrucosa* Ehrh.) wood veneers with nominal thickness of 1.5 mm and moisture content of ~5% were used in this study. Tangential sheets of veneer were cut into 300 mm by 300 mm pieces for the thermo-mechanical densification and subsequent measurements. Veneer sheets without visible defects were selected.

2.2 Short-term thermo-mechanical compression

Veneer sheets were compressed using an automatically controlled single-opening hot press. To avoid surface contamination during compression, veneer specimen was placed between smooth and carefully cleaned thin stainless steel sheets. Then, the veneer specimen between steel sheets was placed between heated press plates and when the pressure reached 0.5, 1.0, 1.5, 2.0, 2.5, 3.0 or 3.5 MPa, the veneer specimen was held under compression perpendicular to the grain (thickness direction) at temperatures of 150 or 180 ℃ for 1 min, and after this period the press was opened, the densified veneer removed from the press and allowed to cool to room temperature. Before and after compression, the weight and dimensions of the specimens were measured. The changes of the densified veneer properties were evaluated by veneer thickness (T_V), weight loss (WL), surface roughness (SR) and density (D_V) measurements.

The compression ratio (CR_V) and densification ratio (DR_V) of the veneer sheets after the pre-compression process were calculated as shown below:

$$CR_V = (T_b - T_a)/T_b \times 100(\%) \quad (1)$$

where CR_V is the compression ratio of veneer, T_b is the thickness of the veneer before compression (mm), and T_a is the thickness of the veneer after compression (mm).

$$DR_V = (D_{Va} - D_{Vb})/D_{Vb} \times 100(\%) \quad (2)$$

where DR_V is the densification ratio of veneer, D_{Vb} is the density of the veneer before compression (kg/m^3), and D_{Va} is the density of the veneer after compression (kg/m^3).

2.3 Surface roughness measurement

The profile surface of veneers was recorded using a portable surface roughness tester (TR200, INNOVATEST). The asperity shape of the surface profile was evaluated with a surface roughness meter by tracing a stylus with tip radius of 2 µm parallel to the grain direction. The measurements were taken over a length of 2.5 mm with a cut-off value of 0.25 in the evaluation of surface roughness, and the surface profile was treated with a Gaussian filter according to ISO 4287 (1997).The following parameters of veneer surface roughness (SR) were evaluated: arithmetic average height (R_a), average peak to valley roughness (R_z), maximum height of the roughness profile (R_t), root mean square (R_q), maximum peak height (R_p), maximum valley depth (R_v), mean width of the profile elements ($RS_m = S_m$ at ISO 4287 1997), mean spacing of local peaks of the profile (S), skewness (R_{sk}).

2.4 Manufacturing of plywood panel samples

Three-layer experimental plywood panels were manufactured from densified veneers using commercial phenol–formaldehyde (PF) adhesive. The solid content matter of the PF adhesive was 49.2%. No additives or fillers were used with the PF adhesive. The PF adhesive was applied manually on the loose side of the veneers with a hand roller-spreader such that the adhesive spread was 100 g/m^2 based on the wet mass. After gluing, three veneer sheets with dimensions of $300 \times 300 \times 1.5$ mm^3 (length × width × thickness) were positioned with the fiber directions perpendicular to each other, and assembled panels were pressed in the laboratory hot press FONTIJNE TP 400 according to the parameters presented in Table 1. The adhesive spread for the test panels was 100 g/m^2 based on the wet mass; that is 33% less than the adhesive spread used for the control panels (150 g/m^2); pressing pressure was 1.0 MPa that is 44.4% less than pressure used for the control panels (1.8 MPa); and pressing time was 3 min, this is 50% less than pressing time used for the control panels (6 min). Such lower values of pressing parameters were chosen because previous studies found that densified wood/veneer provided higher thermal conductivity (Asako et al. 2002) and lower adhesive consumption in the manufacture of plywood compared with non-densified veneer (Bekhta and Marutzky 2007; Bekhta et al. 2009, 2012). Three plywood panels with dimensions of 300×300 mm^2 were manufactured each with veneers uncompressed (control) and compressed at each compression temperature and pressure, resulting in 45 panels. Thereafter, test samples were prepared from these boards: 15 samples per shear strength test and 5 samples per dimensional changes test from each board (a total of 675 samples for shear strength test and 225 samples for dimensional changes test). The water absorption, thickness swelling and shear strength of the manufactured plywood samples were measured according to relevant standard test methods. Plywood manufactured from non-densified veneer sheets was used as the control sample.

Prior to testing, all plywood test samples were conditioned at 20 ± 2 ℃ and $65 \pm 5\%$ relative humidity. Thereafter, the dimensions and weights of the plywood samples were measured to calculate the density of the plywood panels. Compression ratio (CR_P) and densification ratio (DR_P) of plywood panels were calculated as shown below:

$$CR_P = (T_{Veneers} - T_P)/T_{Veneers} \times 100(\%) \quad (3)$$

where CR_P is the compression ratio of plywood panels, $T_{Veneers}$ is the total thickness of all veneers (mm), and T_P is the thickness of the panel (mm).

$$DR_P = (D_P - D_V)/D_V \times 100(\%) \quad (4)$$

where DR_P is the densification ratio of plywood panels, D_V is the density of the veneer (kg/m^3), and D_P is the density of the panel (kg/m^3).

Table 1 Experimental parameters for panel manufacture

Panel type	Pre-compression temperature (℃)	Pre-compression pressure (MPa)	Pressing temperature (℃)	Pressing pressure (MPa)	Pressing time (min)	Adhesive spread (g/m^2)
PC	–	–	145	1.8	6	150
P150	150	0.5; 1.0; 1.5; 2.0; 2.5; 3.0; 3.5	145	1.0	3	100
P180	180	0.5; 1.0; 1.5; 2.0; 2.5; 3.0; 3.5	145	1.0	3	100

2.5 Shear strength test

To compare the ability of the densified veneer for bonding, mechanical tests were performed in plywood panel samples prepared from the non-densified and densified veneer. For each type of plywood, the test pieces for shear strength testing were pre-treated for intended use in exterior conditions according to EN 314-1 (2004). The testing samples were immersed in boiling water for 4 h, dried in a ventilated oven at 60 ± 3 ℃ for 16 h, immersed in boiling water for 4 h, followed by cooling in water at 20 ± 3 ℃ for at least 1 h to decrease the temperature of the test pieces to 20 °C. The samples were tested immediately after the pre-treatments were completed. Ten samples were used for each variant of shear strength mechanical testing.

2.6 Water absorption and thickness swelling test

Dimensional stability in the form of thickness swelling (TS) and water absorption (WA) of the samples were determined according to water soaking test based on EN 317 (1993), using test pieces of dimension 50 × 50 mm^2. They were immersed in distilled water for three different periods of 24, 48 and 72 h. After this time the test pieces were removed from the water, weighed, and the thickness was measured. The percent change from the original thickness represents the thickness swelling, and the percent weight change from the original weight represents the water absorption. The water absorption and thickness swelling of plywood panel samples were calculated according to the following formulae:

$$WA = (W_2 - W_1)/W_1 \times 100(\%) \quad (5)$$

$$TS = (T_2 - T_1)/T_1 \times 100(\%) \quad (6)$$

where W_1 and T_1 = initial weight (g) and thickness (mm) before soaking; W_2 and T_2 = final weight (g) and thickness (mm) after soaking.

2.7 Analysis of variance (ANOVA)

Analysis of variance (ANOVA) at a 0.05 significance level was carried out using IBM SPSS Statistics software to estimate the relative importance of the effects of the study variables such as pre-compression temperature and pressure and their interactions on the veneer and plywood properties.

2.8 Microscopic evaluation of adhesive penetration of the samples

Samples (50 × 50 mm^2 cross section) were cut from the panel to analyze microscopic structure of glue line and effect of veneer pre-compression conditions on adhesive penetration of plywood panels using a stereo microscope (Canon Power Shot SD 1300 IS (IXUS 105), Japan). The image of the samples was viewed according to the desired angle for clearer view images.

3 Results and discussion

3.1 Physical properties of thermally compressed veneer

Mean values of physical characteristics of thermally densified veneers are presented in Table 2. During thermal compression some changes in the physical properties of densified veneers can be observed, in particular, in terms of weight loss and improvement of veneer surface roughness. The ANOVA showed that pre-compression pressure significantly affects the changes in WL, CR_V, DR_V and SR (such as R_a, R_q, R_z, R_p, RS, RS_m) and has no significant effect on the veneer density and SR (such as R_v, R_{sk}). Pre-compression temperature significantly influences the veneer density, WL, CR_V and SR (such as R_a, R_q) and has no significant effect on DR_V and SR (such as R_z, R_p, R_v, RS, RS_m, R_{sk}). The interaction of pre-compression temperature and pressure has significant influence only on the veneer density and WL, and has no effect on other properties of veneer. WL significantly increases with increasing pre-compression temperature and pressure as confirmed by the factor analysis.

In the present study, due to the reduction of veneer moisture during thermal compression from 5.4% to 2.8 and 1.9% (P150 and P180 panel type) (Table 2; Fig. 1), it can be assumed that WL of 3.0 and 3.7% (P150 and P180 panels type) are mainly caused by the dehydration (moisture loss). It would appear that the 1 min duration of thermal compression is not enough time for chemical changes in wood (although at high temperatures 150 and 180 ℃, but the low pressure 0.5–3.5 MPa). In previous studies (Bekhta et al. 2014b, 2017) no chemical changes in wood were observed. Similar results were reported by Rautkari et al. (2010), who using FTIR spectroscopic analysis showed that no significant chemical changes occur during compression using friction.

Table 2 Physical properties (average values) of compressed veneer

Property	Type of plywood panels		
	PC	P150	P180
T_V (mm)	1.53	1.45	1.44
MC (%)	5.4	2.8	1.9
WL (%)	–	3.0	3.7
CR_V (%)	–	3.8	4.7
DR_V (%)	–	0.75	0.97

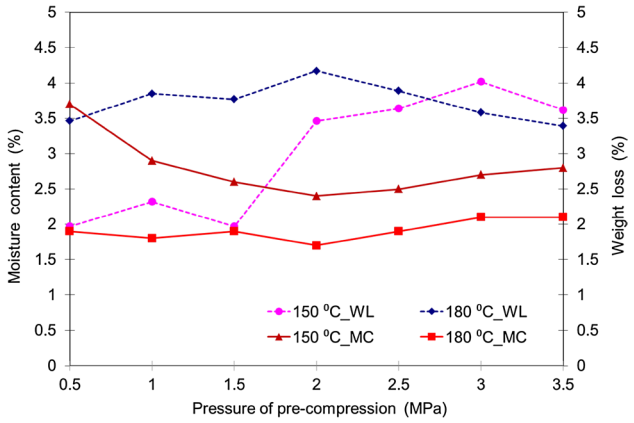

Fig. 1 Effect of pre-compression temperature and pressure on moisture content (MC) and weight loss (WL) of compressed birch veneer

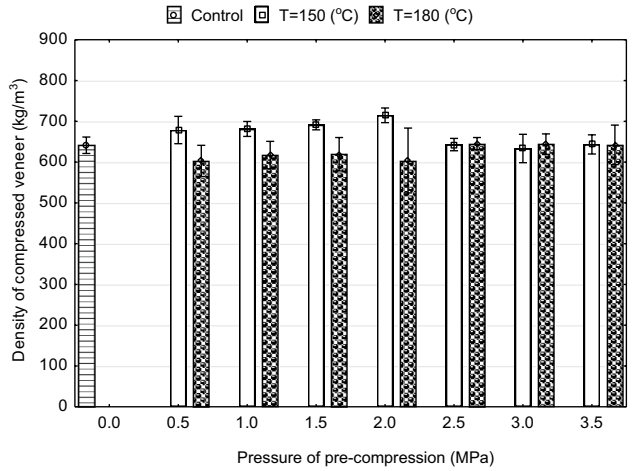

Fig. 2 Effect of pre-compression temperature and pressure on density of compressed birch veneer

Thermal compression reduced the thickness of veneers and, consequently the volume, increasing the density. However, the density of densified veneer (625–669 kg/m^3) in the present study remained virtually unchanged compared with the density of non-densified veneer (641 kg/m^3). Though the thickness of the veneer during thermal compression is reduced, the weight of veneer is also reduced (because of weight loss), and, therefore, the density of veneer was virtually unchanged (Fig. 2). Although CR_V has been affected by temperature and pressure increase, this effect was not observed for density, probably due to WL caused by heat application (Table 2). Arruda and Del Menezzi (2013) also found that thermomechanical densification at pressure 2.7 N/mm^2 and temperatures 140 and 180 °C virtually did not affect the density of densified veneer. In this work, the statistical analysis showed that the increase in pressure from 0.5 to 3.5 MPa did not influence the increase in density. Therefore, the less severe treatment was satisfactory for densification. Statistical analysis also showed that temperature is the major factor affecting veneers' density (D_V).

3.2 Surface roughness

As was expected, pre-compression of veneer led to a reduction in their surface roughness. As can be seen in Table 3, the values of surface roughness were decreased almost twice when pre-compression pressure increased from 0 to 3.5 MPa. Such improvement of surface roughness was observed for both pre-compression temperatures (150 and 180 ℃). The improvement of surface smoothness with increasing press temperature and pressure could be explained by the result of plasticisation of veneer surface; temperatures above 160 ℃ cause transition of lignin in thermoplastic condition that improves densification of the surface layer and increases its density.

Moreover, the surface of the densified wood was smoother because the surface of raw wood has pores and voids. In the densified wood surface, the pores and voids were closed and lathe checks that were present on veneers before densification were conglutinated because of the application of mechanical load and heat (Bekhta et al. 2017).

One of the roughness parameters R_q indicates whether the surface has become smoother; the smaller the value of R_q, the smoother the surface. The depth of the cavities (R_v) practically remains unchanged with increasing pre-compression pressure from 0 to 3.5 MPa, however the height of the peaks of irregularities (R_p) is reduced. As a consequence of these changes, the mean width of profile elements (RS_m) decreased. Therefore, properly densified flat surface helps to ensure that a layer of adhesive of uniform thickness can be uniformly spread over the bonding area and less adhesive should be put on such surface. There is a clear evidence of correlation between pre-compression conditions (pressure and temperature) and surface roughness (Fig. 3). In previous studies (Bekhta and Marutzky 2007; Bekhta et al. 2009, 2012, 2014b) it was also found that pre-compression of veneer (but at higher pressures) allows to obtain a smooth veneer surface with low values of roughness. These data are also well in agreement with the data of other authors (Candan et al. 2010; Diouf et al. 2011; Arruda and Del Menezzi 2013; Buyuksari 2013), who also found a substantial reduction in surface roughness due to thermal compression of wood. It is well known that roughness plays important roles in the process of wood gluing. Hence, surface smoothness of a panel is important for the manufacturing of glue laminated (Faust and Rice 1986) and plywood (Bekhta and Marutzky 2007; Bekhta et al. 2009) panels.

Table 3 Surface roughness parameters of the panels and the results of Duncan's mean separation tests

T (°C)	P (MPa)	R_a (µm)	R_q (µm)	R_z (µm)	R_p (µm)	R_v (µm)	RS (µm)	RS_m (µm)	R_{sk} (µm)
Non-compressed		9.78 (2.22)^{a}	11.95 (2.44)^{a}	49.92 (9.29)^{a}	27.54 (5.86)^{a}	22.38 (4.04)^{a}	0.31 (0.06)^{a}	0.73 (0.17)^{a}	0.44 (0.43)^{a}
150	0.5	7.35 (1.45)^{b}	9.15 (1.91)^{b}	41.58 (8.11)^{ab}	20.15 (5.87)^{b}	21.43 (3.79)^{ab}	0.27 (0.13)^{ab}	0.61 (0.34)^{ab}	−0.04 (0.73)^{ab}
	1.0	6.86 (1.64)^{b}	8.68 (2.18)^{b}	37.22 (10.30)^{bc}	20.36 (8.27)^{b}	16.85 (5.77)^{ab}	0.24 (0.06)^{abc}	0.59 (0.28)^{ab}	−0.06 (1.08)^{ab}
	1.5	6.75 (1.33)^{bc}	8.35 (1.51) ^{bc}	38.21 (4.17)^{bc}	20.04 (5.09)^{b}	18.17 (3.84)^{ab}	0.24 (0.03)^{abc}	0.53 (0.19)^{abc}	0.16 (0.83)^{ab}
	2.0	6.60 (1.14)^{bc}	8.45 (1.38) ^{bc}	36.85 (6.93)^{bc}	17.28 (4.54)^{bc}	19.56 (7.17)^{ab}	0.23 (0.07)^{abc}	0.53 (0.21)^{abc}	−0.24 (1.08)^{ab}
	2.5	6.47 (0.76)^{bc}	8.43 (0.76) ^{bc}	40.26 (3.49)^{ab}	17.08 (2.19)^{bc}	23.18 (2.88)^{a}	0.23 (0.03)^{abc}	0.51 (0.24)^{abc}	−0.71 (0.74)^{b}
	3.0	5.57 (1.29)^{bc}	6.93 (1.57) ^{bc}	29.31 (7.98)^{c}	14.05 (5.78)^{bc}	15.26 (4.95)^{b}	0.19 (0.06)^{bc}	0.39 (0.11)^{bc}	−0.24 (0.88)^{ab}
	3.5	4.89 (1.29)^{c}	6.23 (1.96)^{c}	28.00 (10.71)^{c}	10.91 (3.02)^{c}	17.08 (7.72)^{ab}	0.18 (0.02)^{c}	0.29 (0.02)^{c}	−0.82 (0.26)^{b}
180	0.5	7.47 (1.29)^{c}	9.04 (1.44)^{d}	40.96 (9.40)^{ca}	20.22 (5.09)^{d}	20.74 (5.35)^{a}	0.26 (0.09)^{ba}	0.89 (0.80)^{b}	−0.07 (0.48)^{ba}
	1.0	7.33 (1.35)^{c}	8.83 (1.62)^{d}	39.99 (9.56)^{ca}	20.99 (3.21)^{da}	19.00 (8.92)^{a}	0.25 (0.06)^{ba}	0.71 (0.14)^{ab}	0.44 (0.65)^{a}
	1.5	5.87 (0.58)^{bc}	7.69 (1.32)^{cd}	38.06 (12.21)^{ca}	18.98 (6.76)^{cd}	19.09 (7.01)^{a}	0.25 (0.10)^{ba}	0.47 (0.25)^{ab}	−0.54 (0.75)^{ba}
	2.0	5.19 (0.66)^{b}	7.07 (1.22)^{bcd}	34.49 (7.73)^{bc}	14.82 (6.56)^{bcd}	19.67 (8.21)^{a}	0.21 (0.05)^{b}	0.38 (0.09)^{a}	−0.44 (1.43)^{ba}
	2.5	4.63 (0.36)^{b}	5.69 (0.43)^{bc}	25.65 (2.16)^{b}	11.85 (1.88)^{bc}	13.79 (2.22)^{a}	0.20 (0.04)^{b}	0.37 (0.08)^{a}	−0.29 (0.67)^{ba}
	3.0	4.39 (0.40)^{b}	5.36 (0.43)^{b}	23.35 (2.73)^{b}	9.31 (1.55)^{b}	14.05 (3.90)^{a}	0.18 (0.05)^{b}	0.38 (0.03)^{a}	−0.76 (0.46)^{ba}
	3.5	4.41 (0.57)^{b}	5.82 (0.90)^{bc}	30.51 (7.46)^{bc}	12.21 (2.85)^{bc}	18.30 (5.15)^{a}	0.18 (0.03)^{b}	0.32 (0.09)^{a}	−0.82 (0.47)^{b}

Values in parenthesis are standard deviations

T temperature, *P* pressure

$^{a–d}$Values having the same letter are not significantly different (Duncan test at $p < 0.05$)

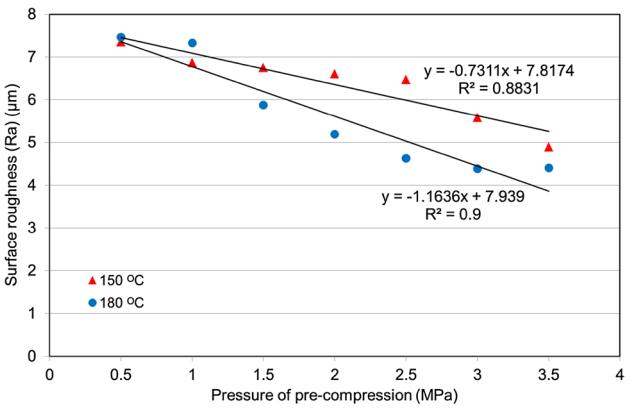

Fig. 3 Correlation between surface roughness and conditions of pre-compression of birch veneer

3.3 Thickness, density, compression and densification ratios of plywood panels

Average moisture content (MC), thickness (T_P), density (D_P) and compression (CR_P) and densification (DR_P) ratios of the samples cut from the corresponding plywood panels are shown in Table 4.

It is obvious that MC of plywood panels containing densified veneer is lower (4.0%) than in control panels (4.4%). The decrease in MC is expected because the thermal compression densified the veneers and reduced the equilibrium moisture content, considerably reducing the number of free hydroxyl groups and accordingly hygroscopicity (Arruda and Del Menezzi 2013), and the possibility of moisture absorption from outdoor environment is reduced.

Table 4 Physical and mechanical properties (average values) of plywood panels

Type of plywood panels	T_P (mm)	MC (%)	D_P (kg/m^3)	CR_P (%)	DR_P (%)	Shear strength (MPa)	WA (%)	TS (%)
PC	4.21 (0.02)	4.4 (0.26)	715 (7.5)	8.4	10.5	1.92 (0.22)^{a}	57.6 (2.9)^{b}	13.14 (0.74)^{b}
P150	4.31 (0.05)	4.0 (0.18)	717 (25.6)	1.1	6.7 (7.4^{d})	2.29 (0.51)^{b}	56.5 (3.2)^{a}	11.79 (0.84)^{a}
P180	4.31 (0.04)	4.0 (0.17)	675 (16.4)	0.6	7.4 (8.4^{d})	2.63 (0.20)^{c}	59.9 (2.7)^{c}	11.78 (0.79)^{a}

Values in parenthesis are standard deviations

$^{a–c}$Values having the same letter are not significantly different (Duncan test at $p < 0.05$)

^{d}Values calculated due to the density of non-densified veneer

The aim of the veneer thickness measurement was to find the effects of the different conditions of densification of veneers on the tolerance of a pressed plywood panel. In the case of veneer compression in the production of plywood it is very important to choose such compression paeameters so that the thickness of finished plywood is within acceptable limits; to avoid unnecessary losses of wood raw material.

It can be seen that average thickness of plywood panels made from pre-compressed veneer at different pressures and temperatures is not less but even higher than the thickness of the control plywood (Table 4) that is essential for industrial application of this technology. Although the average compression ratio (CR_P) of veneer is 3.8% (for 150 ℃) and 4.7% (for 180 ℃) compared with uncompressed veneer. In this case, it would seem that thickness of the plywood containing thermally compressed veneer should be lower. However, plywood panels containing thermally pre-compressed veneer was pressed (Table 1) at much less pressure (1.0 MPa) than the control plywood (1.8 MPa). In this case, the average compression ratio of plywood containing pre-compressed veneer was much smaller 0.6% (for 180 ℃) and 1.1% (for 150 ℃) compared to the compression ratio of 8.4% for control plywood. Therefore, more thickness loss during pre-compression of veneer sheets might result in less compression during hot-pressing of plywood. Moreover, plywood containing pre-compressed veneer was manufactured with 33% less adhesive spread than the adhesive spread used for the control panels. Therefore, its compression ratio will be much smaller, since less moisture brought with adhesive into pack of veneer, and such pack, in turn, is less densified (wood is deformed harder). In addition, thermal compression of veneer leads to its drying (the moisture is removed under press pressure and temperature). Accordingly, such veneer will be harder (worse) densified in the hot pressing process of plywood. Plywood panels P150 show identical tolerances to plywood panels P180.

The European Standard EN 315 (2000) specifies tolerances of unsanded plywood panels for nominal thickness of 4 mm as −0.4 mm (min) and +0.8 mm (max), respectively; i.e. the thickness of the finished unsanded plywood panels should be within 3.6–4.8 mm. In this study, the values of plywood thickness were 4.26 and 4.31 mm for panels made from non-densified and thermally densified veneers, respectively (Table 4), and they do not go beyond tolerances for unsanded panels in accordance with this standard.

Moreover, it is well known that after pressing of plywood the obtained panels have a tendency to return to original dimensions of veneer pack (set) before pressing. There is some "springback" (2–5%) on unloading (Sheldon and Walker 2006), i.e. limited return to original dimensions. The extent of springback is dependent upon a number of factors, such as the process parameters used in the pre-compression process of veneer as well as the pressing process of plywood. During pressing of plywood at higher pressure (1.8 MPa) and adhesive spread rate (150 g/m^2) using conventional (non-densified) veneer sheets, a high CR_P (8.4%) and DR_P (10.5%) can be observed (Table 4). Under such pressing conditions, the densification of veneer is great and, as a result, the deformations of veneer are high, and these deformations are transformed into permanent deformations. The thickness of the plywood panel, resulting from the pressing process, is fixed with adhesive (glue bonds between the veneer and adhesive). In this case, the elastic forces of the veneers are insufficient to return the panel to the original thickness of veneer package. Thus, the elastic recovery (springback) in this case is insignificant and the final thickness of the pressed panel is low in comparison with densified veneer.

The DR_P (6.7 and 7.4% for PC150 and PC180, respectively) of plywood panels made from thermally densified veneer was higher than CR_P (1.1 and 0.6% for PC150 and PC180, respectively) of these panels at the same conditions. The reasons for this are that CR_P takes into account only the thicknesses of the veneer packs and panels while DR_P takes into account also the weight of panel (sum of weights of wood, moisture and adhesive) as well as the thicknesses.

Figure 4 reveals that the density values of plywood panels decreased with increasing pre-compression temperature of veneers under the mentioned conditions. The plywood containing veneers pre-compressed at a temperature of 180 °C showed the lowest density values (675 kg/m^3). In contrast, the plywood manufactured from veneers pre-compressed at a temperature of 150 ℃ and non-densified veneers had the highest densities (715 and 717 kg/m^3, respectively). Some increase in densities of P150 plywood panels in comparison with PC and P180 plywood panels for pre-compression pressures 0.5–2.0 MPa (Fig. 4) may be explained by the

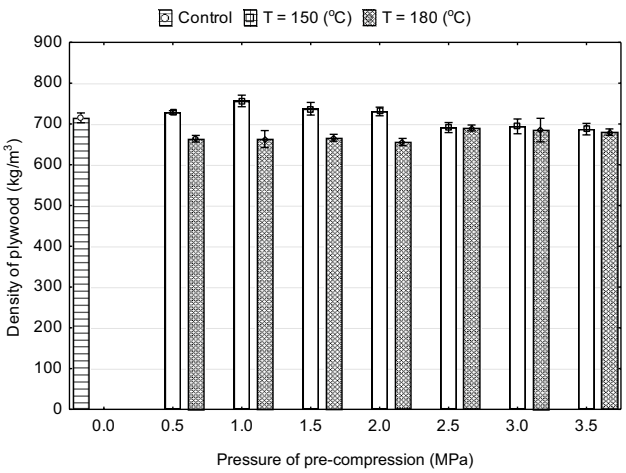

Fig. 4 Density of the plywood panels made from uncompressed veneer and veneer pre-compressed at different pressures and temperatures

influence of other unpredictible technological factors, for example anatomical structure of wood veneer, and especially higher densities of veneer prior to compression, rather than the compression pressures. Moreover, as already mentioned above, the control plywood panel (PC) was produced with pressing parameters that are recommended by plywood producers—pressure 1.8 MPa and adhesive spread 150 g/m^2. Small amount of adhesive (for example 100 g/m^2), which was used for panels with densified veneer, is very hard to apply evenly on the rough surface of the conventional uncompressed veneer. Plywood with compressed veneers (PC150 and PC180) was produced at lower pressure (1.0 MPa) and smaller adhesive spread (100 g/m^2) in view of the recommendations received from previous works (Bekhta and Marutzky 2007; Bekhta et al. 2009, 2012). In these works, it was shown and established that adhesive spread of 150 g/m^2, which is usually recommended for rough veneer, is not suitable (too high) for smooth compressed veneer because the surface pores are closed and thickening of the adhesive layer occurs. It is known that with increasing glueline thickness the bonding strength decreases; with a thicker glueline, higher internal stress is generated during glue shrinkage which can lead to the lower shear strength of plywood. Both plywood panels of thermally compressed veneers (at 150 and 180 °C) and non-densified veneers had higher density values than birch solid wood for veneer production. The reduction in density for plywood made from veneers pre-compressed at a temperature of 180 °C is probably caused by the following factors: (1) lower amount of plywood thickness loss during pressing due to lower pressure and adhesive spread used; (2) lower compression ratio of plywood during pressing due to lower pressure and adhesive spread used, and thereafter lower moisture content; (3) increased veneer weight loss during short-term pre-compression process due to the dehydration.

3.4 Dimensional stability (water absorption and thickness swelling)

Hot pre-compression of veneer sheets improved the dimensional stability of the plywood panels. Plywood made from thermally densified veneer was more dimensionally stable than plywood made from non-densified veneer. The results of water absorption and thickness swelling of plywood panels after 24, 48, and 72 h of immersion in water are presented in Figs. 5 and 6. Plywood panels made from both non-densified and densified veneers showed an increase in water absorption after 24, 48, and 72 h of immersion in water. However, the plywood panels containing densified veneers show relatively low TS as compared to panels containing non-densified veneer. Among the treated groups, the panels pressed with veneer densified at 180 °C had the lowest TS values for 24, 48, and 72 h. The highest TS values were obtained from control panels with 24, 48, and 72 h water soaking time.

The pre-compression pressure and temperature affected WA and TS. As the pre-compression pressure and temperature increased, the WA rates increased. TS increased with the rising of pre-compression pressure, while pre-compression temperature did not significantly affect TS. The application of a higher pre-compression pressure at the same temperature level increased the amount of TS of plywood panels, suggesting it is not necessary to apply higher pre-compression pressures to enhance the dimensional stability of panels. An increase in TS values with increasing pre-compression pressures of veneer is explained by an increasing springback effect due to the higher internal stresses induced during densification (Anshari et al. 2011; Unsal et al. 2011).

WA of plywood from thermally pre-compressed veneer was normally higher in comparison with using non-densified veneer (Fig. 5). However, it should be noted that influence of compression temperature and pressure on the WA process was different. WA was smaller for a temperature of 150 °C and pressures in the range of 0.5 to 2.0 MPa compared with the control samples. However, at the highest investigated pressures (2.5–3.5 MPa) at the same temperature, the WA values were higher than for control samples. Again, these changes in WA values were closely related with appropriate changes of panels' density (see Fig. 4). It is known fact that WA of panels decreases with increasing their densities (Sheldon and Walker 2006), because there are less internal cavities in panels of high density than in lower density panels. Therefore, WA of higher density plywood is mainly due to the permeation of moisture inside cells, and this process occurs much slower than the filling of cavities by moisture. Moreover, the phenolic resin also protected some areas from allowing water to diffuse into the plywood sample. For the same pre-compression pressure WA increased with temperature rises from 150 to 180 °C, which can be explained by the increase of panels' density. For pre-compression temperature of 180 °C for all investigated pressures the WA was higher compared with control samples due to lower density of veneer (see Fig. 2). Higher WA values can easily be associated with lower density of panels (see Fig. 4) and accordingly with a porous structure where more water can be absorbed by cell walls and cavities of cells.

In a previous work (Bekhta et al. 2016), the appearance of small spherical-like droplets in the surface of the cell wall was observed by the microscopic analysis of thermally compressed alder veneer. It was assumed that these spherical droplets were condensation compounds of lignin and degradation products of hemicelluloses. The increase in lignin absorbance is clearly detectable by the changes in color (brown) of the evaluated densified veneer samples (Bekhta et al. 2014a). Since lignin is a hydrophobic substance, it helps to decrease the WA and TS of plywood

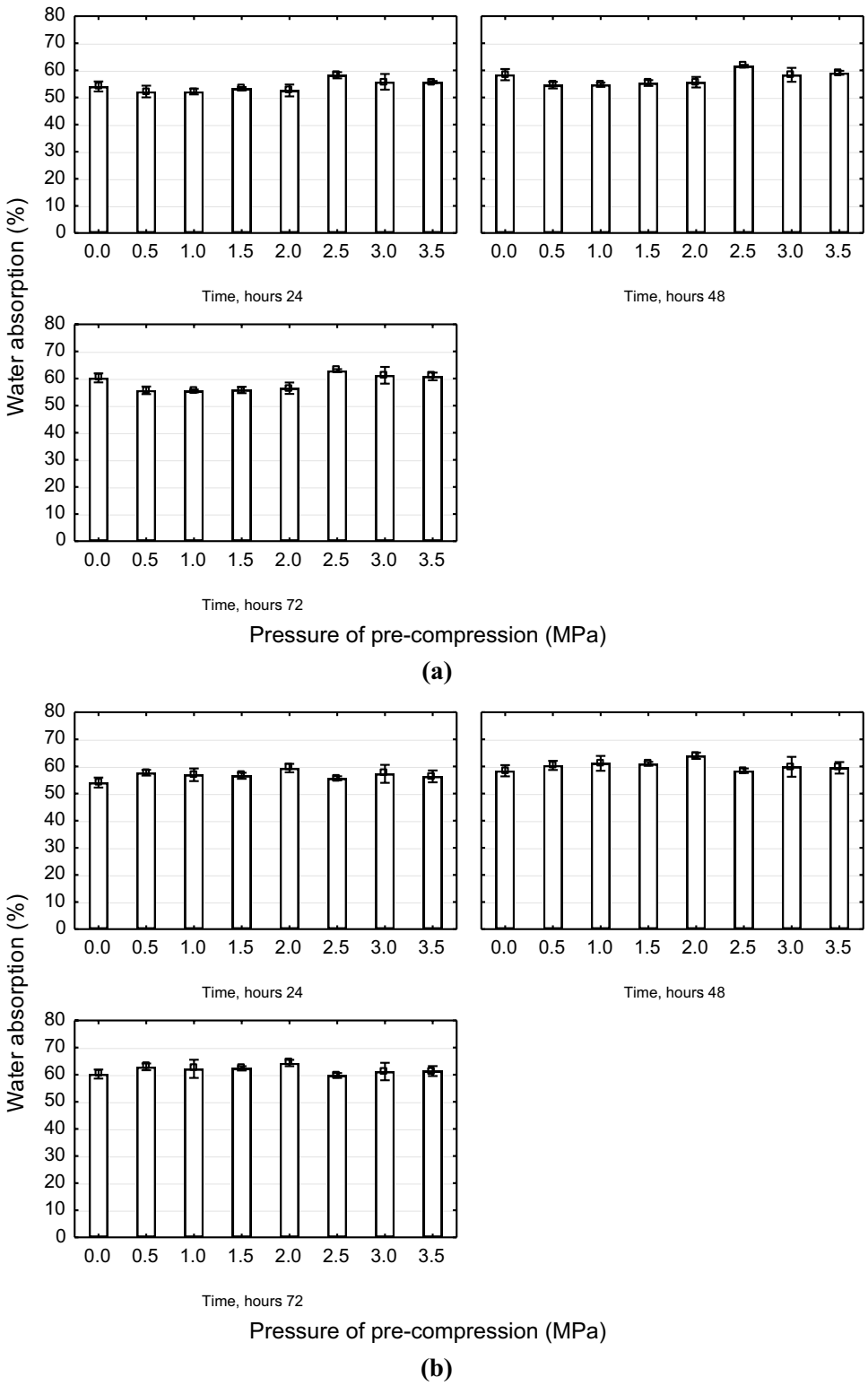

Fig. 5 Water absorption of the plywood panels made from veneer pre-compressed at **a** 150 °C; **b** 180 °C

samples. Furthermore, it can be assumed that during thermal compression, extractives diffuse to the veneer surface where they can concentrate and physically repel water (since they are also hydrophobic), increasing the hydrophobicity of the surface of wood veneers.

One of the most important measurements of wood's affinity for water is the contact angle. The measurements of contact angle in earlier works (Bekhta and Krystofiak 2016; Bekhta et al. 2017) showed that the contact angle of thermally densified veneers increased with increasing

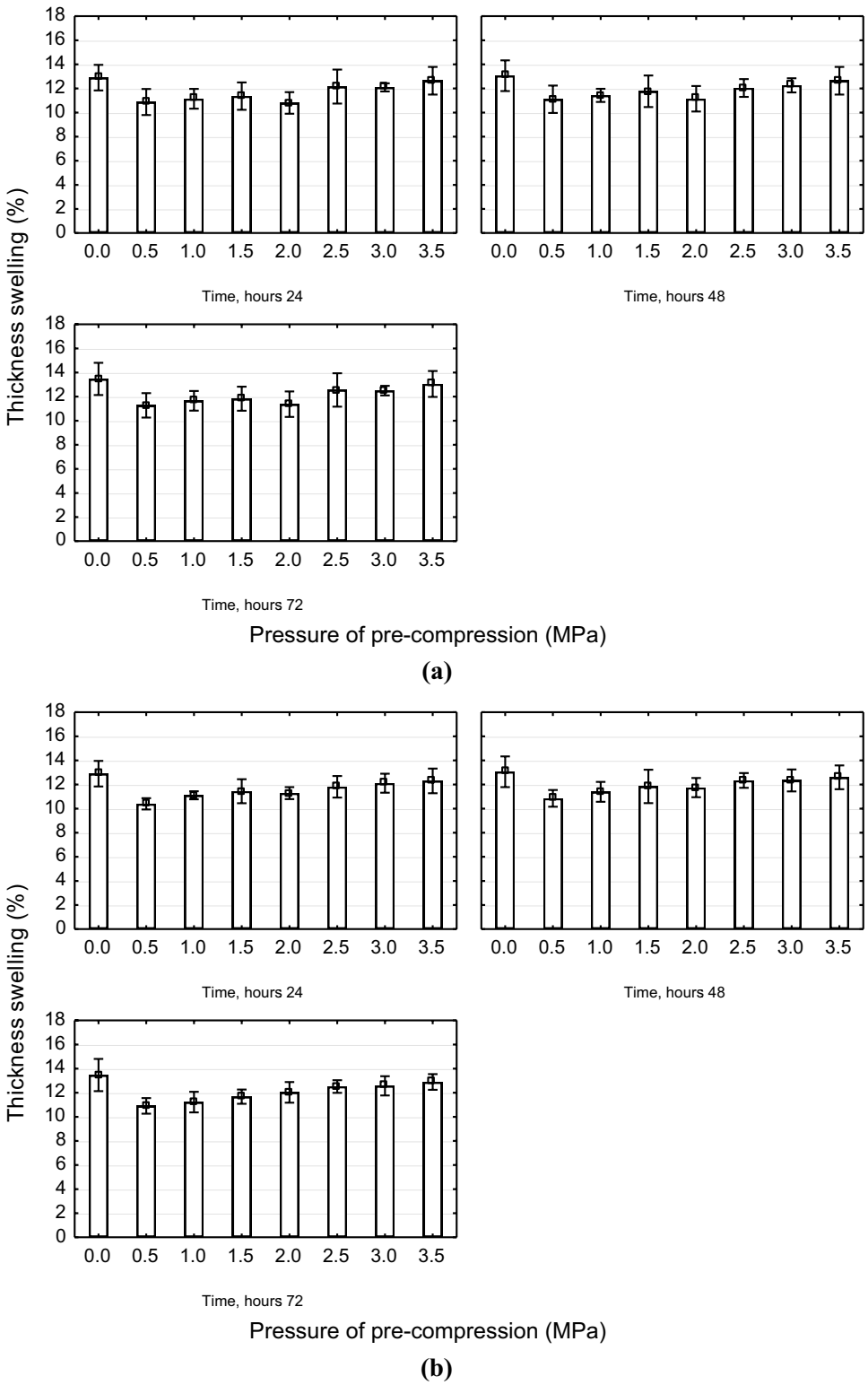

Fig. 6 Thickness swelling of the plywood panels made from veneer pre-compressed at **a** 150 °C; **b** 180 °C

densification temperature and pressure, which indicated decreasing affinity for water by densified material. A previous study (Unsal et al. 2011) showed that the hardness of wood increased during the densification process. Such a high increase in hardness might be due to the closing of the vessel and fiber lumens. Consequently, it could be assumed that the increased surface hardness of densified veneer also reduces its ability to absorb water.

Therefore, the reasons for improving the dimensional stability of plywood panels made from thermally

pre-compressed veneer were expressed as follows: (1) changes of panels' density; (2) increasing hydrophobicity of veneer surface and associated deterioration of wetting by water; (3) increasing lignin ratio; (4) increasing surface hardness.

3.5 Shear strength

The shear strength of plywood samples improved at higher pre-compression temperatures of 150 and 180 °C (Fig. 7), both being higher than for control samples. Moreover, it was found that shear strength of plywood panels made from veneer pre-compressed at 180 °C was higher than from veneer pre-compressed at 150 °C (Table 4). It is possible that the boiling water test had a greater effect on plywood panels from non-densified veneers, so the shear strength for these test conditions shows lower resistance in control plywood panels. From the presented data it is clear that the plywood made of the densified veneers proves corresponding shear strength values in comparison with the controls, despite the lower adhesive spread (100 g/m^2) and lower pressing pressure (1.0 MPa). It is worth noting that bond quality is fully satisfactory and meets EN 314-2 (1993) requirements.

Although the effect of pressure on the shear strength is significant, the lowest and highest values of strength are only slightly different as for the temperature of 150 °C (2.01–2.61 MPa) as well as for the temperature of 180 °C (2.51–2.74 MPa) with increasing pre-compression pressure from 0.5 to 3.5 MPa. From a technological point of view, this fact is very important because in a production scale, it will be possible to apply lower pre-compression pressure. This allows saving wood (not overrun wood) due to its slight densification.

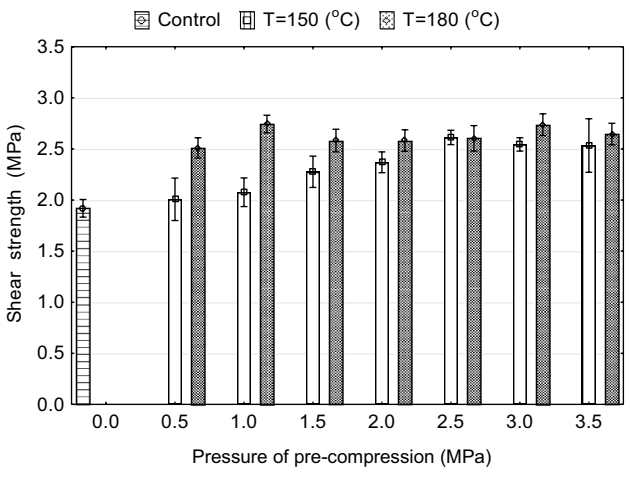

Fig. 7 Shear strength of the plywood panels made from uncompressed veneer and veneer pre-compressed at different pressures and temperatures

Similar findings were obtained in previous works (Bekhta and Marutzky 2007; Bekhta et al. 2009, 2012), where satisfactory shear strength of plywood panels made from pre-compressed veneer was also achieved at lower adhesive consumption and press pressure, and this was explained by the improvement of surface roughness of densified veneer. It is well known (Sheldon and Walker 2006) that rotary-cut veneer sheets are characterized by the presence of small checks, called lathe checks, on the loose side of the veneers; no checks are present on the other side (tight side) of the sheet. During the glue process, the tight side is glued onto the loose side of the veneer; therefore, the irregularities on the surface are filled by adhesive. It can be considered that the irregularities on the surface are increased by the perpendicular joining of two veneers in plywood with non-densified veneers. This situation increases the adhesive quantity applied and therefore decreases glue-line resistance in plywood panels. When the veneers are densified and then glued in plywood panels, the irregularities decrease by adjusting the checks on the surface of veneers. Therefore, empty spaces in the sheets decrease and glue-line resistance increases.

In this work, there was only clear evidence of a moderate correlation between shear strength of plywood panels and surface roughness of densified veneer (Fig. 8), probably due to the many other interacting variables influencing the results. In other words, the results of this study give reason to assert that in order to provide high bonding strength it is not enough to have veneer with low surface roughness values. Obviously, the adhesive spread will be of great importance for pre-compressed veneer of uniform thickness and free from deep checks, with densified and smooth surface, since the thickness of the glueline is dependent on the adhesive spread. Parallel and flat surfaces allow the adhesive to flow freely and form a uniformly thin layer of adhesive that is essential for the bonding quality. Furthermore, the bond

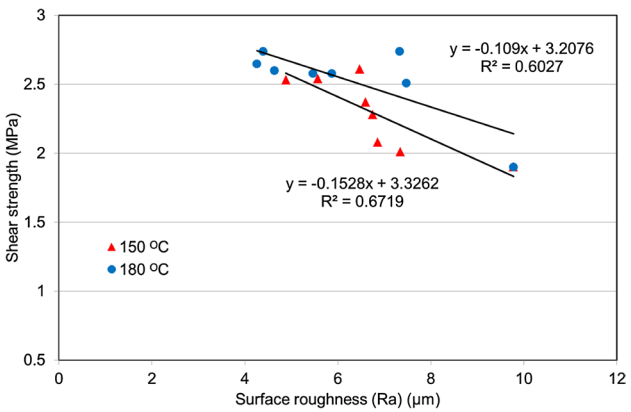

Fig. 8 Correlation between shear strength of plywood panels and surface roughness of veneer

strength between two veneer surfaces is determined by the wood with related parameters (like density, porosity, surface hardness, moisture content, strength of the wood tissue, or grain angle), by the properties and penetration behaviour of the adhesive, the adhesive mix as well as the bonding processing parameters. Other factors like pH and extractive components of the wood are also important since they can interfere with adhesive curing time during the pressing process of the panels in the hot press.

However, it is still questionable whether the higher shear strength of plywood panels containing densified veneers is derived from: (1) an improved smoothness of veneer surface; (2) a thinner glue line (due to a lower glue consumption) introducing less stress concentrations when the adhesive has cured, and accordingly high cohesive strength; (3) from a good contact, and accordingly the effective bonding area and shear strength can actually be higher between smooth and flat densified veneer surfaces than between rough and uneven non-densified veneer surfaces; or (4) from a uniform spreading of adhesive and/or distribution of adhesive of uniform thickness over the bonding area and accordingly formation of uniformly thin layer of adhesive; the thicker adhesive film shrinks and fractures more than the thinner one and may contain more voids from entrapped solvent gases.

3.6 Microscopic analysis of the samples

It was observed (Fig. 9) that the adhesive was not distributed evenly on plywood panels made from non-densified veneer due to the effects of its rough surface in comparison with plywood panels made from densified veneer. The non-densified veneer has a loose structure with many checks existing on the surface as veneer peeled from a log. Penetration into spread loose sides is deeper and less uniform. The penetration of adhesive more deeply into loose sides of non-densified veneer is attributable to entry via the lathe checks on the former, which furthermore make this side weaker than the loose side in densified veneer. The pre-compression technique applied at earlier stage of the panel production has made the surface become smoother and denser with decreasing amount of adhesive spread rate. As previously reported herein, lathe checks that were present on veneers before densification were conglutinated and veneer surface roughness decreased under the influence of heat and pressure.

4 Conclusion

Based on the findings of this study, the pre-compression of veneer prior to adhesive application resulted in improved physical and mechanical properties of plywood panels. Moreover, thermal pre-compression generates some changes in the properties of densified veneer. In particular, weight loss and improvement of surface roughness of veneer was observed. In addition, pre-compression conditions significantly influence the density, compression and densification ratios of veneer. There was a clear evidence of a strong correlation between pre-compression parameters (temperature and pressure) and surface roughness of veneer.

The obtained results showed that water absorption and thickness swelling of plywood panels made from densified veneer were significantly improved. The plywood made of densified veneers shows relatively low water absorption and thickness swelling in comparison to the panels made of non-densified veneer. The shear strength values of plywood panels made of densified veneer were greater than those of plywood panels made of non-densified veneer. It was also found that shear strength of panels made from veneers pre-compressed at 180 ℃ was higher than from veneers

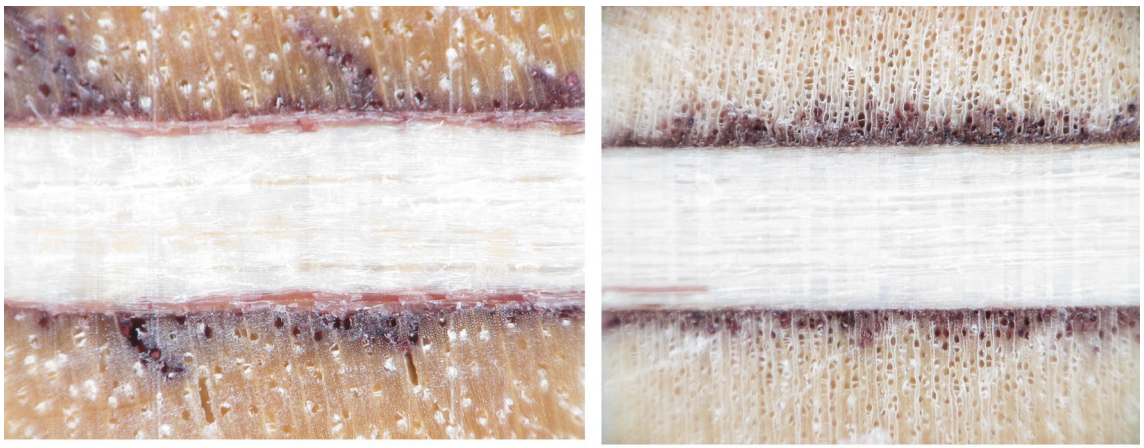

Fig. 9 Images of glue lines of plywood panels made from non-densified (**a**) and densified (**b**) veneer

pre-compressed at 150 ℃. The shear strength of tested plywood panels meets standard EN 314-2 requirements even with reduced (a 33% reduction) adhesive spread. In this work, only clear evidence of a moderate correlation between shear strength of plywood panels and surface roughness of densified veneer was observed, probably due to the many other interacting variables influencing the results.

The average compression ratio of plywood made from pre-compressed veneers was much lower, 0.6% (for 180 °C) and 1.1% (for 150 °C) compared to the compression ratio (8.4%) for control plywood samples. The thickness tolerances of obtained plywood panels were within acceptable limits for unsanded panels in accordance with the standard EN 315. This result is essential for industrial application of this pre-compressed technology of veneer before adhesive application avoiding unnecessary losses of wood raw material. Moreover, the hot pre-compression of veneer considerably influences all operations of the technological process of the manufacturing of plywood, reduces the time of pressing (a 50% reduction), pressure of pressing (a 44.4% reduction), and adhesive spread (a 33% reduction), and there is also an opportunity of the economy of fine wood due to the reduction of sanding (*i.e.* due to smoother wood surface).

Acknowledgements The authors acknowledge COST Action FP1303 "Performance of bio-based building materials" for support of STSM-FP1303-010615-060045. This work was supported by the Slovak Research and Development Agency under the contract no APVV-14-0506 and APVV-15-0235. Special thanks are extended to Ing. B. Lizoň for making microscopic images of veneer samples surfaces before and after densification.

References

Anshari B, Guan ZW, Kitamor A, Jung K, Hassel I, Komatsu K (2011) Mechanical and moisture-dependent swelling properties of compressed Japanese cedar. Constr Build Mater 25(4):1718–1725

Arruda L, Del Menezzi CHS (2013) Effect of thermomechanical treatment on physical properties of wood veneers. Int Wood Prod J 4(4):217–224

Asako Y, Kamikoga H, Nishimura H, Yamaguchi Y (2002) Effective thermal conductivity of compressed wood. Int J Heat Mass Transf 45(11):2243–2253

Bekhta P, Krystofiak T (2016) The influence of short-term thermomechanical densification on the surface wettability of wood veneers. Maderas-Cienc Technol 18(1):79–90

Bekhta PA, Marutzky R (2007) Reduction of glue consumption in the plywood production by using previously compressed veneer. Holz Roh Werkst 65(1):87–88

Bekhta P, Hiziroglu S, Shepelyuk O (2009) Properties of plywood manufactured from compressed veneer as building material. Mater Des 0(4):947–953

Bekhta PA, Niemz P, Sedliačik J (2012) Effect of pre-pressing of veneer on the glueability and properties of veneer-based products. Eur J Wood Prod 70(1):99–106

Bekhta P, Proszyk S, Krystofiak T (2014a) Colour in short-term thermo-mechanically densified veneer of various wood species. Eur J Wood Prod 72(6):785–797

Bekhta P, Proszyk S, Krystofiak T, Mamonova M, Pinkowski G, Lis B (2014b) Effect of thermomechanical densification on surface roughness of wood veneers. Wood Mater Sci Eng 9(4):233–245

Bekhta P, Proszyk S, Lis B, Krystofiak T (2014c) Gloss of thermally densified alder (*Alnus glutinosa* Goertn.), beech (*Fagus sylvatica* L.), birch (*Betula verrucosa* Ehrh.), and pine (*Pinus sylvestris* L.) wood veneers. Eur J Wood Prod 72(6):799–808

Bekhta P, Mamonova M, Sedliačik J, Novák I (2016) Anatomical study of short-term thermo-mechanically densified alder wood veneer with low moisture content. Eur J Wood Prod 74(5):643–652

Bekhta P, Proszyk S, Krystofiak T, Sedliačik J, Novák I, Mamonova M (2017) Effect of short-term thermomechanical densification on the structure and properties of wood veneers. Wood Mater Sci Eng 12(1):40–54

Burmester A (1973) Effect of heat-pressure treatments of semidry wood on its dimensional stability. Holz Roh Werkst 31:237–243

Buyuksari U (2013) Surface characteristics and hardness of MDF panels laminated with thermally compressed veneer. Compos Part B-Eng 44:675–678

Buyuksari U, Hiziroglu S, Ayrilmis N, Akkilic H (2012) Mechanical and physical properties of medium density fiberboard panels laminated with thermally compressed veneer. Compos Part B-Eng 43(2):110–114

Candan Z, Hiziroglu S, Mcdonald AG (2010) Surface quality of thermally compressed Douglas fir veneer. Mater Des 31(7):3574–3577

de Melo RR, Del Menezzi CHS (2014) Influence of veneer thickness on the properties of LVL from Parica (*Schizolobium amazonicum*) plantation trees. Eur J Wood Prod 72:191–198

Diouf PN, Stevanovic T, Cloutier A, Fang C-H, Blanchet P, Koubaa A, Mariotti N (2011) Effects of thermo-hygro-mechanical densification on the surface characteristics of trembling aspen and hybrid poplar wood veneers. Appl Surf Sci 257:3558–3564

EN 314-1:2004. Plywood. Bonding quality. Part 1: test methods. European Committee for Standardization, Brussels

EN 314-2 (1993) Plywood. Bonding quality. Part 2: requirements. European Committee for Standardization, Brussels

EN 315 (2000) Plywood. Tolerances for dimensions. European Committee for Standardization, Brussels

EN 317 (1993) Particleboards and fibreboards. Determination of swelling in thickness after immersion in water. European Committee for Standardization, Brussels

Faust TD, Rice JT (1986) Effect of veneer surface roughness on gluebond quality in Southern pine plywood. For Prod J 36(4):57–62

ISO 4287 (1997) Geometrical product specification (GPS). Surface texture: profile method. Terms, definitions and surface texture parameters. International Organization for Standartization, Geneva

Laine K, Rautkari L, Hughes M, Kutnar A (2013) Reducing the set-recovery of surface densified solid scots pine wood by hydrothermal post-treatment. Eur J Wood Prod 71(1):17–23

Rautkari L, Hughes M, Properzi M, Pichelin F (2010) Properties and chemical changes of surface densified wood. In: Proceeding of the 11th World Conference on Timber Engineering, Trees and Timber Institute, National Research Council, Trentino, Italy, 20–24 June 2010, pp. 235–237

Richter K, Feist WC, Knabe MT (1995) The effect of surface roughness on the performance of finishes. Part 1: roughness characterization and strain performance. For Prod J 45(7/8):91–97

Sheldon S, Walker J (2006) Wood-based composites: plywood and veneer-based products. In: Walker J (ed) Primary wood processing: principles and practice, 2nd edn. Springer, New York, pp 391–426

Tenorio C, Moya R, ·Muñoz F (2011) Comparative study on physical and mechanical properties of laminated veneer lumber and plywood panels made of wood from fast-growing *Gmelina arborea* trees. J Wood Sci 57:134–139

Unsal O, Candan Z, Buyuksari U, Korkut S, Chang Y-S, Yeo H (2011) Effect of thermal compression treatment on the surface hardness, vertical density propile and thickness swelling of eucalyptus wood boards by hot-pressing. Mokchae Konghak 39(2):148–155

Welzbacher CR, Wehsener J, Rapp AO, Haller P (2008) Thermo-mechanical densification combined with thermal modification of Norway spruce (*Picea abies* Karst) in industrial scale—dimensional stability and durability aspects. Holz Roh Werkst 66:39–49