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ORIGINAL

Simultaneous drying and densification of silver birch (*Betula pendula* L.) veneers: analysis of morphology, thickness swelling, and density profile

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Abstract In this study, birch (*Betula pendula* L.) veneers were simultaneously densified and dried using a contact drying method at pressures of 1.5 and 3 MPa at 130 °C and compared with veneer dried in a laboratory-scale convective type dryer. Compression rate, thickness swelling, and the density profiles of the veneers were investigated. Furthermore, the microstructure of densified veneers was studied by scanning electron microscopy (SEM). A maximum veneer compression rate of 9 % was achieved at a pressure of 3 MPa. Under these conditions, the veneers were, on average, densified from 504 to 574 kg m^{-3} (approximately 14 %). After water soaking, full set-recovery—recovery to the initial thickness—occurred. However, the swelling rate was lower for the densified veneer. Density profiles measurements showed that densification occurs throughout the veneers. The SEM images showed that the surface of the densified veneers were smoother, whilst no cracks were detected due to densification. Densification seemed to occur in vessels. Typically, rays were bent when there was a vessel nearby.

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Introduction

Over the years, several wood modification techniques, which mainly concentrated on the modification of solid wood, have been developed (Hill 2006). Veneer modification has received less attention. One of the modification techniques is wood densification (Navi and Sandberg 2012). The densification of the veneers could have excellent potential to improve veneer and plywood properties. Densified veneers could be used, for example, either on the surfaces of the plywood or the whole plywood could be made of densified veneers.

Different methods have, in the past, been used for the densification of veneers. Plywood made from densified veneers with good properties has previously been reported. Fang et al. (2012) and Cloutier (2008) densified trembling aspen (*Populus tremuloides*) and hybrid poplar (*P. maximowiczii* × *P. balsamifera*) with a thermo-hydro-mechanical (THM) process, using a steam injection hot press. Veneers were pre-treated with steam at a line pressure of 0.6 MPa. Four temperatures (160, 180, 200, and 220 °C) and hydraulic pressures of between 4.5 and 9 MPa were used depending on the target thickness. The theoretical compression set was 50 %. Fang et al. (2012) found that lathe checks were conglutinated and the veneers were darker when a higher temperature was used. The Brinell hardness of densified veneers was about two to three times higher, and bending and tensile strengths were increased by approximately 30–40 % depending on the pressing temperature. Set-recovery, that is the recovery to the initial thickness after water soaking, decreased with increasing compression temperature. At a temperature of 220 °C, there was almost no set-recovery. Diouf et al. (2011) also densified trembling aspen (*P. tremuloides*) and hybrid poplar (*P. maximowiczii* × *P. balsamifera*) using the same process as Fang et al. (2012). They found that densification resulted in major chemical changes of the veneer surfaces mainly at temperatures higher than 160 °C and caused a significant reduction in wettability and a decrease in surface roughness.

Bekhta and Marutzky (2007) compressed beech veneers with moisture content (MC) of 7.2 %, at pressures of 5, 10, and 15 MPa at 200 °C. The surface roughness of veneers was reduced as the compression pressure was increased. Consequently, the amount of adhesive needed to bond the veneer could be reduced from 200 to 150 g m^{-2} whilst achieving even better bond performance. The shear strength after 24 h cold water immersion was higher by 15 %. Furthermore, Bekhta et al. (2012) pressed rotary-cut birch (*Betula pubescens*) veneers, equilibrated to RH 65 % and 20 °C, at pressures of 3, 5, 7, and 9 MPa, and temperatures of 100, 150, and 200 °C and compared the surface roughness and shear strength of plywood produced using these. In their study, the smoothest surfaces were obtained with a densification process using 9 MPa pressure at 200 °C for a period of 2.0 min. When using a low (90 g m^{-2}) amount of adhesive, a clear dependence between surface roughness and shear strength was found. The shear strength of plywood increased when surface roughness decreased. Therefore, Bekhta et al. (2012) concluded that in plywood production with densified veneers, a lower amount of adhesive, reduced pressure, and probably reduced pressing time could be used. Candan et al. (2010) also noticed that there was a clear improvement in surface quality when Douglas-fir

(*Pseudotsuga menziesii*) veneer, conditioned at RH 65 % and 20 °C (MC 12 %), was compressed in a hot press using pressure levels of 1.0, 2.0, and 2.5 MPa and temperatures of 180 and 200 °C.

Bekhta et al. (2009) used a laboratory-scale cold rolling press to compress dry (MC 8 %) birch (*B. pubescens*) veneer of nominal thickness 1.5 mm and studied the perpendicular and parallel-to-grain tensile strength. The perpendicular-to-grain tensile strength of the veneer was highest at a compression ratio (CR) of 10 %. Tensile strength parallel-to-grain still increased by approximately 12 % when increasing the CR from 10 to 25 %. When plywood was made from these veneers, its shear strength was highest at a CR of 15 % and almost the same when the CR was 10 %. The bending strength of the plywood behaved in the same manner as shear strength.

From the literature, it can be seen that almost all of the previous veneer densification procedures have been carried out on dry veneer (i.e. conditioned at RH 65 % and 20 °C), resulting in veneers with a MC of 12 % or lower. The only exception seems to be Lui et al. (2013) who used a viscoelastic thermal compression (VTC) process (Kamke and Rathi 2011) with an integrated drying step prior to veneer densification. From an energy consumption and process capacity point of view, it should be beneficial to simultaneously dry and densify veneers.

When MC is high, the glass transition temperature T_g of the amorphous component of cellulose, hemicelluloses, and lignin is below 100 °C (Salmén 1982), with water acting as a plasticizer, decreasing the interactions between hemicelluloses and lignin macromolecules and the amorphous regions of the cellulose (Navi and Sandberg 2012). From a material point of view, it would be beneficial to compress veneers in high MC and dry them after compression. The studies described above clearly show that there is strong potential to improve veneer and plywood properties by the densification process.

Lahti et al. (2010) and Paajanen et al. (2012) developed a contact drying method for veneer drying, which utilizes a vacuum-press technique. The technique is essentially the same as the vacuum-press dewatering method used for the heat treatment of massive wood (Hofmann et al. 2013). The main aim of the current study was to examine the suitability of this contact drying method (Paajanen et al. 2012; Holmberg et al. 2009) for veneer modification by densification, where wet veneers are dried and densified at the same time. The target was to densify veneers by a maximum of approximately 10 %, because in an earlier study (Bekhta et al. 2009), it had been found that this CR is optimal to maximize strength. A further aim of this study was to investigate the suitability of an X-ray densitometer to measure the density profile of veneer. The density profiles of veneers densified under different conditions were evaluated to assess the location (surface or core) of the densification in the whole cross-section.

Materials and methods

Two fresh birch (*Betula pendula* L.) logs with an average diameter of 30 cm and length of 130 cm were soaked at 40 °C for 48 h and peeled with a rotary lathe

(Model 3HV66; Raute Oyj, Lahti, Finland). The initial average ($n = 5$, 8 measurements/veneer sheet) wet thickness of the veneers was 1.59 mm with a standard deviation of 0.02 mm, and the initial average MC (measured gravimetrically) was 82.6 % with a standard deviation of 3.4 %. Prior to drying, the veneers were cut into 400 × 400 mm^2 sheets. There were a small number of knots in the veneer sheets.

Veneer drying and densification

Reference veneers were dried using a laboratory-scale convective type veneer dryer (Raute Oyj, Lahti, Finland), at 160 °C for approximately 4.5 min until 0 % MC was reached. Veneer densification was performed using the contact drier described by Paajanen et al. (2012). The apparatus is illustrated schematically in Fig. 1. It was built as an experimental system, where the press is used to ensure good contact between the veneer and the heating plate. However, by increasing the pressure, the device can also be used in veneer densification.

The apparatus has a steel heated top plate, which is in direct contact with the veneer. The bottom platen, where the veneer is in contact with a wire surface, is supported by an aluminium frame and is cooled by a water circulation system below the supports. The drying chamber can be sealed and vacuum introduced if needed. The use of vacuum speeds up the drying process. The cooled bottom plate is the major difference compared with traditional contact veneer driers (Holmberg et al. 2009).

The integrated compression and drying procedure was performed using different temperatures and pressures as listed in Table 1. The degree of softening of the lignin, hemicelluloses, and the semi-crystalline cellulose was expected to be different for each treatment (Navi and Sandberg 2012; Salmén 1982). Accordingly,

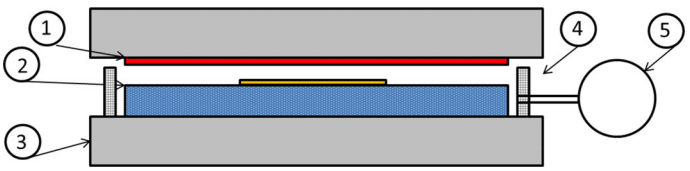

Fig. 1 Schematic illustration of the contact dryer; *1* hot top plate, *2* cooled bottom plate, *3* press, *4* vacuum chamber seal, and *5* vacuum pump

Table 1 Veneer drying and densification parameters

Code	Drying type	Pressure (MPa)	Temperature (°C)	Drying/pressing time (min)
Control	Convective	0	160	4.5
P1.5T4	Contact	1.5	160	4
P3T10	Contact	3.0	130	10
P3T15	Contact	3.0	130	15

the purpose of the different treatments was to achieve different CRs. Furthermore, to show drying as a function of time, veneers (five replicates for each time interval) were dried for 30, 60, 120, 180, 240, and 300 s, taken out of the press, weighed and subsequently oven-dried at 103 °C for 24 h, enabling the average MC to be calculated at each time interval.

The thickness of the veneers was measured with a digital micrometer (Mitutoyo ID-C112 PB, Japan) combined with an instrument that ensures the veneer is flat when measured. After peeling the veneer, the green thickness was measured. After the treatments, the veneers were oven-dried, and then the dry thickness was measured. The CR was calculated using Eq. 1.

$$\mathrm{CR} = \frac{t_{\mathrm{wet}} - t_{\mathrm{dry}}}{t_{\mathrm{wet}}} \tag{1}$$

where t_{wet} is thickness of the wet veneer, and t_{dry} is thickness of the dry veneer.

Dynamic thickness swelling

Prior to the dynamic swelling measurements, the compressed veneers were conditioned at an RH of 15 %, 40 °C until equilibrium was reached. The veneers were cut into 100 × 100 mm^2 ($n = 5$) sections and then placed in water at room temperature. Thickness was measured after soaking for 2, 4, 6, 8, 10, and 15 min. After soaking, the veneers were again conditioned at RH 15 %, 40 °C until equilibrium had been reached, and the thickness re-measured. The MC of the veneers at RH 15 %, 40 °C was, on average, 3.8 % ($n = 20$).

Density profile measurements

The veneers were conditioned (RH 65 %, 20 °C) before the density profile measurements were conducted. The density profile analysis was conducted using an X-ray densitometer (QMS, Model QDP-01), where X-ray attenuation is assumed to be proportional to density. In this experiment, the narrow X-ray beam was projected through the tangential direction of the veneer, and then scanned in the thickness direction to produce the density profile. The specimens were cut into 13 × 50 mm^2 (tangential × longitudinal) specimens, unlike previous research where specimen size was 50 × 50 mm^2 for density profile measurements (Rautkari et al. 2011a, b, c, 2013). This change was made because the thin veneer was rather curved and smaller dimensions enabled the specimens to be clamped flat in the densitometer. Ten specimens of each veneer type were measured at intervals of 0.02 mm through the thickness.

Additionally, densified veneer was examined with a scanning electron microscope (SEM) (Zeiss ΣIGMA VP). The surface was dry-cut using a microtome (Leica EM UC7) at room temperature. An Emitdec K100X sputter coater was used to apply gold to the veneer samples before SEM analysis.

Results and discussion

Figure 2 shows the veneer MC as a function of time. An exponential decay model was fit to these results (MC = 0.23–70.99exp(−t−2.60)/93.86, adjusted $R^2 = 0.97$). The results suggest that at the beginning (up to $t = 30$ s), drying is faster than predicted by the exponential relationship, which can probably be attributed to the evaporation of free water. Below the fibre saturation point (FSP), the drying curve seems to follow an exponential trend. After 300 s drying time, veneers are at zero MC with very small deviation. Hukka and Oksanen (1999) found a similar drying time for 1.5 mm jet-dried birch veneers.

After the drying (and densification), the density of the veneers was determined. Table 2 shows the gravimetrically measured densities of the samples, on which the density profiles were also based and the CRs determined.

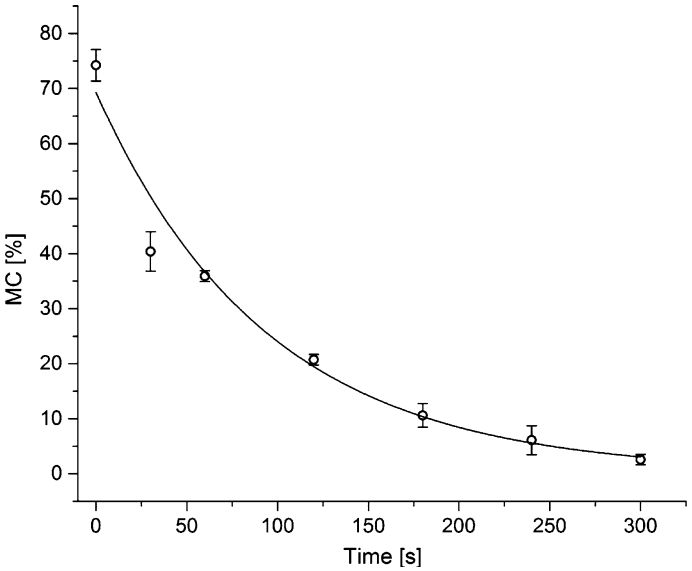

Fig. 2 MC as a function of time at the contact drying machine, (P1.5T4) (*bars* are ±1 standard deviation)

Table 2 Average ($n = 11$) veneer density (oven-dry) measured gravimetrically and compression ratio (CR)

	Density (kg m^{-3})	CR (%)
Control	504 (9)	5.0
P1.5T4	520 (4)	8.6
P3T10	574 (45)	13.5
P3T15	563 (29)	13.5

Standard deviations are in parentheses

In the case of convective drying, the control specimens, the CR is just the result of shrinking during drying. When CR is adjusted for shrinkage, the CR of the densified veneer is approximately 4–9 %, where 10 % was the target for the highest compression pressure. Some compression also occurred when contact drying with a lower pressure (1.5 MPa), but this was not significant.

In Fig. 3, the first point is dry thickness at RH 15 %, 40 °C. During the water soak test, the control and P1.5T4 specimens reached equilibrium, reaching the final thickness after 2 min of soaking whilst the P3T10 and P3T15 groups continued to increase but at a slower rate (Fig. 3). The drop in thickness for the control veneers after 5 min may be interpreted as measurement inaccuracy. The precision of the measurements was 0.01 mm. After 10 min, swelling had ceased. Table 3 shows the veneer thickness after the dynamic swelling test and conditioning at RH 15 % and 40 °C.

After the dynamic swelling testing and subsequent drying, compression set-recovery is almost complete because the thickness of the compressed veneers is almost the same as un-compressed veneers. Fang et al. (2012) reported that in aspen veneers densified at 160 °C, most of the compression set-recovery

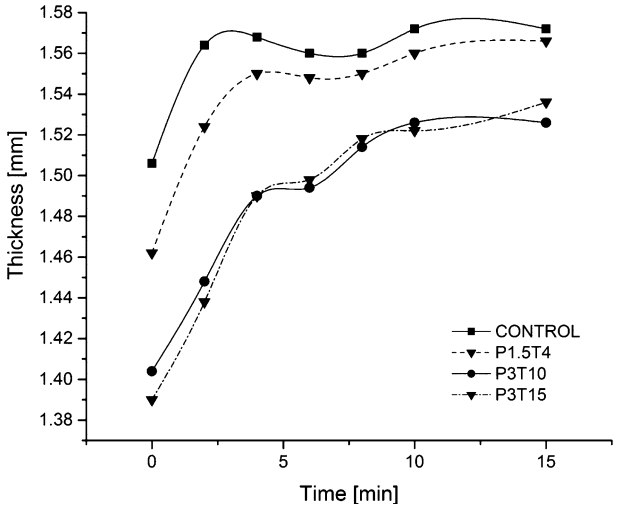

Fig. 3 Average ($n = 5$) thickness variation during dynamic swelling test of different veneer treatments

Table 3 Average ($n = 5$) veneer thickness in dry equilibrium state (RH 15 %, 40 °C) before and after dynamic swelling test. Standard deviations are in parentheses

	Thickness (mm)	
	Before	After
Control	1.51 (0.03)	1.52 (0.01)
P1.5T4	1.46 (0.02)	1.51 (0.01)
P3T10	1.40 (0.01)	1.49 (0.02)
P3T15	1.39 (0.02)	1.49 (0.02)

occurred after the first soaking and oven-drying cycle. In that study, the highest compression set-recovery was approximately 60 % after the first cycle, whilst in the current study, set-recovery was 100 % for the control veneers and 94 % for the most highly densified veneers.

Somewhat similar results have been found in earlier studies (Rautkari et al. 2010) for compressed solid wood. This means that the compression is totally or almost totally reversible at these pressing temperatures (130 and 160 °C). It is well known that the cell walls store elastic strain energy during compression, and the set-recovery effect occurs because the internal stresses are relieved when the wood is exposed to humid or wet conditions. In the last decades, this phenomenon and the elimination of set-recovery, have been studied rather intensively (Navi and Sandberg 2012; Kutnar and Kamke 2012a; Laine et al. 2013). The set-recovery could be eliminated by, for example, further thermal modification or by resin impregnation.

Density profiles

The average density profiles ($n = 8$) of conventionally dried veneers (control) and compression dried veneers, using three different drying parameters (P1.5T4, P3T10, and P3T15), are presented in Fig. 4. The density profile of conventionally dried veneers unsurprisingly shows rather constant density throughout the thickness. The low density recorded at the surfaces is most probably measurement error caused by the slightly uneven surface of the material. However, the high-pressure-compression-dried veneers (P3T10 and P3T15) have clearly been densified when compared

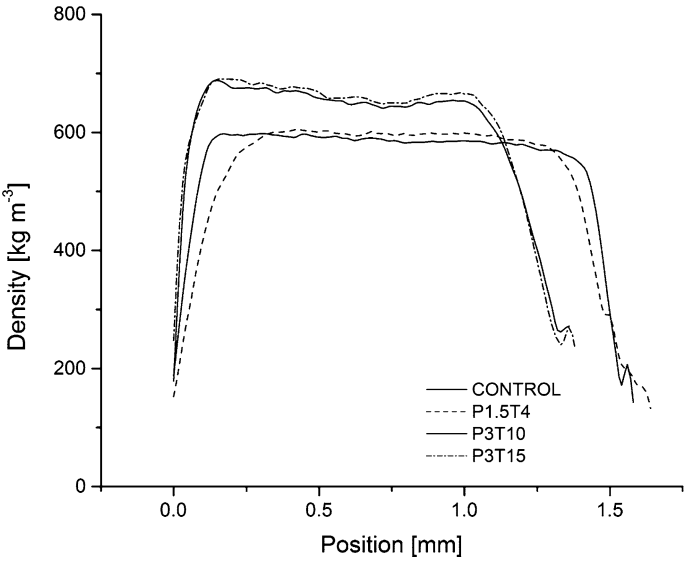

Fig. 4 Average ($n = 8$) density profiles of convective dried veneers (control) and compression dried veneers (P1.5T4, P3T10, P3T15). *Top side* (in contact with heated plate) is on the *left*

to conventionally dried veneers, as shown by the significantly higher plateau region. Compression-dried veneers using low pressure (P1.5T4) are slightly different to the conventionally dried veneers in that only a minor change at the surface is apparent. This effect is most probably caused by the surface drying and low pressure used in compression drying as seen more clearly in an earlier study by Rautkari et al. (2011a). Recently, the same phenomenon has been simulated using FEM with similar results (Fortino et al. 2013).

The statistical differences in density profiles (Fig. 4) between the control and densified veneers were tested with a one-way ANOVA, and further comparison of groups was performed with the Tukey–Kramer test. The one-way ANOVA shows a statistical difference ($\alpha = 0.05$) of gravimetric density between veneer treatments. Further, the Tukey–Kramer multiple comparison test shows that the control group (convective drying) and normal contact drying (P1.5T4) statistically form one group, and both densified veneer types form another group (P3T10 and P3T15).

The microstructure (Fig. 5) of veneer dried in the conventional dryer, and veneer dried and densified in the contact dryer was compared using a SEM. Figure 5b shows that some of the vessels are slightly collapsed (for clarity marked with arrows). The cell walls are not broken, and there are no cracks between cells. Densification seems to be mainly manifested in the vessels. In Fig. 5b, the rays are bent and this appears to be associated with the collapse of the vessels. The bent rays and collapsed vessels occur in the interior of the veneer, which is consistent with the

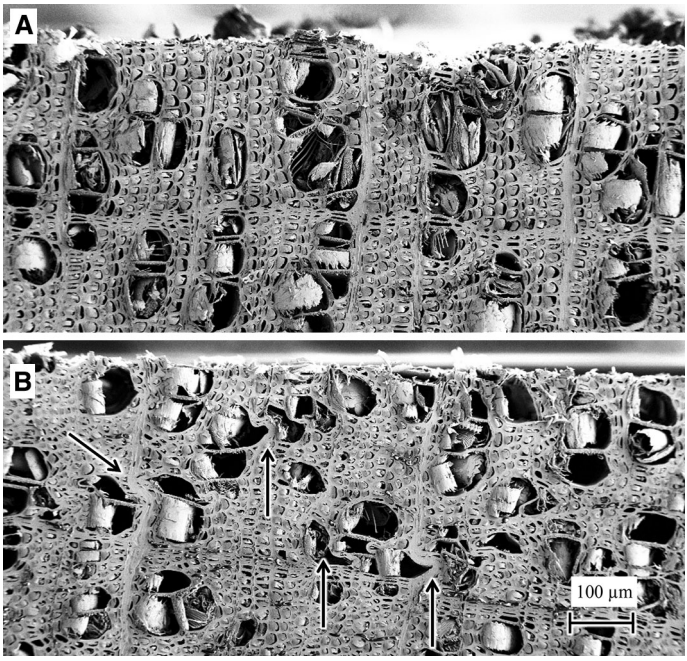

Fig. 5 SEM image of **a** control, convective dried veneer and **b** densified veneer, P3T15 (pressure 3 MPa, pressing time 15 min)

density profiles. The surface of the densified veneer seems to be smoother than un-densified veneer, which suggests that it might be easier to process (press and glue) as found by Bekhta et al. (2012). An earlier study (Rautkari et al. 2009) found a similar smoothing effect in surface densified solid wood.

Heat and mass transfer during the press drying process results in transient temperature, gas pressure, and MC gradients in the veneer, which are analogous to hot-pressing of wood composite panels. The fundamental principles of the viscoelastic behaviour of the wood cell wall can be used to explain the stress relaxation process. Stress relaxation is promoted by increasing the time at increased temperature (Dwianto et al. 1999). Some explanations of the effect of steam and heat on wood in transverse compression have been proposed by Kutnar and Kamke (2012b). The conditions of compression influence the build-up of residual internal stresses, stress relaxation, thermal decomposition, the development of chemical bonds in the cell wall, and loss of hygroscopicity (Kutnar et al. 2009).

Variations in temperature and MC inside the specimens during the veneer drying process were not measured, due to the low thickness of the specimens. However, it can be speculated that the drying process caused stress relaxation in the wood, which resulted in the lower shrinkage ratio of the contact dried veneer.

Conclusion

Based on the findings of this study, veneers can be dried and densified simultaneously using the contact type veneer drier. When drying and densification are performed at the same time, energy and process time could be saved.

The dynamic swelling test showed that densification slows the rate of swelling, whilst the recovery of the compression deformation is complete after water soaking. The density profile measurements did not reveal much variation through the thickness. A slightly higher density near the veneer surface that was in contact with the heated plate was found. SEM images revealed that the surface of the densified veneer was smoother than the control veneer, and the cell structure of densified veneers was undamaged. Densification of birch is mainly confined to collapse of vessels within the range of densification studied.

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