Received: 29 September 2021

Revised: 20 October 2021

Accepted: 8 November 2021

Influence of Veneer Density on Plywood Thickness and Some Mechanical Properties

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Abstract. It has been common knowledge that as the density of wood increases, the mechanical properties also improve. In turn, the density of wood depends on many factors, including the wood moisture content, location and cross-section in the trunk, the type of treatment and the parameters of technological processes. There is a great deal of research reported in the scientific literature on the effect of solid wood density on mechanical properties for different wood species as well as for structural timber. However, no research data can be found related investigation of the influence of veneer density on the properties of the birch plywood.

In the present study, researching the properties of 7-ply birch plywood (thickness 9 mm), it was concluded that as the density of veneers increases, the bending properties of plywood in the direction of wood fibers (covered veneers) increases. When determining the plywood gluing quality, similar tendencies have been observed. For plywood with a lower density in all veneer plies the gluing quality (tensile-shear test) for perpendicular wood fiber veneers increases in the direction from the symmetry axis or middle veneer to the plywood outer plies, which can be explained by the fact that the outer plies become denser at the time of the hot pressing process. The results of the study will allow birch plywood manufacturers in direct production, sort veneers by density, to produce plywood with very predictable gluing quality, plywood thickness and mechanical properties in bending.

Keywords: birch veneer, pressing degree, 3 point static bending, gluing quality.

Introduction

The production of plywood and its related products occupies a rather important segment in the Latvian forest industry sector, and it has particularly developed in recent years, since it is considered to be one of the best - most economically advantageous ways to use birch wood. Due to the fact that birch is one of the dominant tree species in Latvia - 30% (Ministry of Agriculture Republic of Latvia, 2021), it has a particular importance of use.

The use of wood in construction in Europe has tripled its market share compared to the level in 2010, and plywood is one of wood products used for this purpose (Forest-based Sector Technology Platform, 2013). Due to the wide application of plywood in construction, its physical and, in particular, mechanical properties are important. The production of plywood from differently arranged veneers makes it possible to produce the plywood that meets different application requirements. Plywood can be formed with different predictable mechanical properties using a constant thickness and number of the veneers, varying with veneer lay-up schemes. Therefore, the veneer lay-up schemes will certainly depend on the specific application of the plywood,

i.e. the type of the load to which it is intended to be exposed during the use of the plywood. (Popovska Jakimovska, Iliev, & Zlateski, 2017).

In order to ensure more efficient use of raw materials in plywood production, more attention should be paid to raw material influencing properties (veneer densities, moisture content, etc. properties) and direct production processes should be improved - raw material primary processing, veneer and plywood further processing modes. If direct manufacturing processes have been studied quite extensively so far, both in scientific publications (Li *et al.*, 2014; Mirski, Dziurka & Łęcka, 2010) and in the students' final theses (Kinderevičs, 2019; Liepa, 2020), then the research results on how the quality of the raw material - veneers influences various properties of plywood, especially in the Baltic region, have not been widely researched (Kallakas *et al.*, 2020; Shupe *et al.*, 1997).

Plywood is an engineered wood-based panel material glued from an odd number of plies of veneer so that its properties are balanced in relation to the central ply and where the adjacent plies have a perpendicular fiber direction. Plywood as a wood material is heterogeneous, and the

strength of plywood can be considered to depend mainly on the properties of the veneer. Therefore, it is necessary to create plywood to reaching as uniform mechanical properties as possible in all directions of the plywood panel.

The choice of plywood pressing pressure depends on the density of the wood, moisture and other factors (Wang and Dai, 2005). Plywood has a density of at least 15% higher than that of solid wood (Spulle, 2003). The average density of birch plywood is 680 kg m^{-3} (Finnish forest industries federation, 2002).

The gluing of plywood is carried out at increased temperatures and by pressing under pressure, as a result of which the plies of veneer, especially the top ones, are compressed; therefore, the density of plywood depends on its thickness. Thinner plywood, when subjected to pressure during the gluing process, will compress more than thicker plywood (Spulle, 2003). As the thickness of the plywood increases, the loss in its thickness during pressing decreases. The loss of plywood thickness during pressing is also affected by the moisture content of the veneer - the higher it is, the greater the loss of plywood thickness during gluing - the plywood is more compressed.

The above mentioned should be taken into account if veneer plies of lower density and of the same thickness are used for the manufacturing of plywood, assuming that the plies will be more compressed and the actual final thickness of the plywood will not meet the lower thickness limit according to the standard (LVS EN 315, 2000) and the requirements set in manufacturers' handbooks (Finnish forest industries federation, 2002; Latvijas Finieris, 2020).

As the ratio of juvenile wood to mature wood increases, the mechanical properties of the sample decrease because juvenile wood has thinner cell walls, a higher amount of lignin, lower content of cellulose, and lower density (Kretschmann, 2008; Nawrot *et al.*, 2012).

The strength of plywood with the traditional veneer lay-up scheme and an odd number of veneers, is higher in the direction of the outer veneer wood fibers, due the direction of these veneer wood fibers is a match.

If it is necessary to increase the strength of plywood in this direction, plywood can be formed with special lay-up schemes (Lipinskis & Spulle, 2011; Kallakas *et al.*, 2020). Such lay-up schemes complicate the technological process and therefore traditionally plywood is made of a mutually perpendicular arrangement of veneer fibers.

The choice of plywood design determines the dimensional stability in different service classes and the identical mechanical properties in both directions - parallel and perpendicular to the length. This is more the case for plywood with a thickness of more than 18 mm. The thinner the plywood, the greater the differences in its mechanical properties between the sequence of the same thickness but different directions of the veneer fibers in the plywood (Lipinskis and Spulle, 2011).

Another way to increase the density of veneers is pre-pressing (rolling). The production of plywood from pre-pressed (rolled) veneers allows one to save up to 25% of adhesive, to halve the roughness of veneer and plywood and to produce plywood with 22% lower pressure. However, the thickness of the plywood decreases for non-pre-pressed veneer from 8.3 till 6.4 to 8.0 mm for pre-pressed veneer, and the density increases from 793 kg m^{-3} till 807 to 1005 kg m^{-3} , respectively. The reduced pressing pressure and adhesive consumption can be explained by the reduced roughness

parameters $R_{\max}$, R_z , R_s and the increased degree of compression of the veneers from 0 to 15% (Bekhta & Marutzky, 2007).

The thickness of the plywood and its actual tolerances depend on the increased densification of the veneer and pressing degree of the plywood at the time of hot pressing, and this must be taken into account when developing the technology of plywood production. All of the above mentioned factors can significantly affect the mechanical properties of plywood. However, if direct production processes have so far been studied and described relatively extensively, both in scientific publications (Aydin & Colakoglu, 2008; Cristescu *et al.*, 2015; Li *et al.*, 2014) and in the master students' thesis (Kinderevičs, 2020), the study results on how the quality of raw materials - veneers influences various properties of plywood, are relatively insufficient.

In order to use plywood as a structural material in load-bearing structures, it is necessary to ensure appropriate mechanical properties, which are determined by subjecting the plywood to tests for mechanical properties - bending, pressing and tensile strength (Spulle, 2003).

The shape stability of wood materials also depends on the ratio and properties of early and latewood (Kretschmann & Cramer, 2007). Since plywood consists of several plies of veneer, with different densities, it can be assumed that the effect of the density of each ply of veneer is generally reduced.

To test this, the present study has been carried out with the aim of determining the effect of veneer densities on the ultimate strength of the formed plywood in static bending (LVS EN 310, 2001). The obtained empirical data have been processed using mathematical data analysing methods.

Materials and Methods

Characteristic of plywood and preparation of the samples

Rotary-peeled birch veneers with nominal dimensions: length width thickness: 600 600 1.5 mm without visual wood defects were used for the study and placed in a conditioning chamber (air humidity $65 \pm 5\%$, temperature $20 \pm 3 \text{ }^{\circ}\text{C}$) until the mass of the veneers no longer changes. After conditioning, the average moisture content of the veneers $11 \pm 1\%$ were determined and the average thickness of each rotary-peeled veneer was determined. The average thickness was determined from four measurements taken at the corner of each peeled veneer. The mass of each veneer was investigated. The density of each veneer was calculated. Veneers were divided into 2 groups: veneers with a lower density (from 500 to 599 kg m^{-3}) and veneers with a higher density (from 600 to 699 kg m^{-3}). The density of each veneer was marked by writing it on the surface of the veneer. In order to evaluate the maximum effect of veneer density, 2 sample groups were created for the study:

- all 7 lower density (502 to 540 kg m^{-3}) veneer plies, sample group marked as LOWEST;
- all 7 higher density (644 to 690 kg m^{-3}) veneer plies, sample group marked as HIGHEST.

Taking into account the fact that the veneer lay-up scheme also has an effect on the bending strength of plywood, 2 more sample groups were created for the study:

- inner 3 lower density (560 to 582 kg m^{-3}) veneer plies (Figure 1), outer 2 higher density (616 to 626 kg m^{-3}) veneer

plies, sample group marked as HIGHER;

- inner 3 higher density (613 to 636 kg m⁻³) veneer plies (Figure 1), outer 2 lower density (544 to 599 kg m⁻³) veneer plies, sample group marked as LOWER.

The plywood density of these two groups of samples in plywood was reduced to assess whether such a small

difference in density in such a lay-up scheme (Figure 1) affects the mechanical properties of plywood bending and gluing quality, as well as to compare results with sample gluing groups HIGHEST and LOWEST.

Figure 1. Veneer lay-up scheme:
↔, ↔ –direction of wood grain.

Before applying of the adhesive all veneers were dried till moisture content $5 \pm 1\%$. An average amount of adhesive of 150 g m^{-2} was applied to six veneers, using a roller to spread the adhesive evenly over the entire veneer surface. For gluing of plywood phenol formaldehyde (PF) resin adhesive was used. Before placing in the press, the thickness of each plywood pack with the adhesive was determined. The average thickness was determined from four measurements taken at the corner of each plywood pack. Each pack was weighed to determine the actual adhesive consumption. One group of 7-ply rotary-peeled veneer plywood was placed in a press and glued using the following pressing parameters: press plate temperature 135°C , pressing pressure 2.0 MPa , and holding time under pressure 9 min. A gluing press JOOS RDP 150, produced by company Gottfried Joos Maschinenfabrik GmbH & Co. was used for the gluing of the plywood.

Determination of plywood thickness and pressing degree

After removal from the press, the mean thickness of each glued plywood was determined, measured at all four corners. The following formula was used to calculate the pressing degree of plywood in the gluing process:

$$CR = \frac{T_v - T_b}{T_v} \cdot 100,$$

where: CR – pressing degree, %;

T_v – thickness of plywood before gluing, mm;
 T_b – thickness of plywood after gluing, mm.

Determination of bending properties and gluing quality

After gluing, plywoods were placed in a conditioning chamber under constant climatic conditions (relative humidity $65 \pm 5\%$; air temperature $20 \pm 3^\circ\text{C}$) until the mass of the samples no longer changed. After moisture equalization,

samples for bending were made with the dimensions - width and length of $50 \times 230 \text{ mm}$, respectively, 20 samples in the direction of the fibers, 20 samples perpendicular to the fibers (Table 1). Each testing sample was weighed and actual dimensions were determined for the determination of the average density of the plywood gluing group according to the formula accordance standard LVS EN 323 (2000).

A universal testing device ZWICK Z100/TL3S, produced by Zwick Roell group was used to determine the three-point static bending strength and modulus of elasticity (LVS EN 310, 2001) with measurements accuracy regarding standard requirements. The loading speed was selected, so that the sample would collapse within 60 ± 30 seconds. After the destruction of the sample, all samples were placed in the oven to determine the average humidity of each plywood gluing group according to the formula included in the standard LVS EN 322 (1999).

Determination of gluing quality (tensile-shear test) using the loading scheme in compliance with the standard LVS EN 314-1 (2005). Considering that the phenol formaldehyde resin adhesive used in the study is intended for use in outdoor service class, the pre-treatment of the samples should be performed according to the moisture class in compliance with the standard LVS EN 314-2 (2000). Tests were performed on all three intended pre-treatment types (20 samples per one test per each perpendicular veneer ply or 2nd, 4th and 6th veneer ply):

- immersion in water for 24 h at a temperature of $20 \pm 3^\circ\text{C}$;
- immersion in boiling water for 4 h, followed by drying in a ventilated drying oven for 16 to 20 at a temperature of $60 \pm 3^\circ\text{C}$, then repeated immersion in boiling water for 4 h, followed by cooling in water at a temperature of $20 \pm 3^\circ\text{C}$ for at least 1 h;
- immersion in boiling water for 72 ± 1 hours, followed by cooling in water at a temperature of $20 \pm 3^\circ\text{C}$ for at least 1 hour.

After determining the quantitative indicators of the gluing quality (tensile-shear strength), the quality indicator - wood failure of each sample and each plywood tested group was determined. To determine the mechanical properties, a universal testing device ZWICK Z100/TL3S, produced by company Zwick Roell group, and measurements accuracy

regarding standard LVS EN 314-1 (2005) requirements were used.

The marking of samples group and number test pieces by investigated method is shown in Table 1.

Table 1

Marking of samples group and number of test pieces by investigated method

Plywood group description	Group marking	Number of glued ply-woods	Number of samples LVS EN 310, 2001 (parallel to fibers)	Number of samples LVS EN 310, 2001 (perpendicular to fibers)	Number of samples LVS EN 314-1, 2005 (pre-treatment 5.1.1.)	Number of samples LVS EN 314-1, 2005 (pre-treatment 5.1.3.)	Number of samples LVS EN 314-1, 2005 (pre-treatment 5.1.4.)
lower density veneers (502 to 540 kg m ⁻³)	LOWEST	7	20	20	60	60	60
higher density veneers (644 to 690 kg m ⁻³)	HIGEST	7	20	20	60	60	60
inner lower density veneers (560 to 582 kg m ⁻³), outer higher density veneers (616 to 626 kg m ⁻³)	HIGHER	7	20	20	60	60	60
inner higher density veneers (613 to 636 kg m ⁻³), outer lower density veneers (544 to 599 kg m ⁻³)	LOWER	7	20	20	60	60	60

ANOVA t-test was used to determine the significance of the difference between the mean values of the groups of plywood samples. MS Excel and SPSS Statistic20 computer programs were used to process the empirical data obtained in the study.

Results and Discussion

Determination of plywood thickness and pressing degree

When testing the moisture content of the plywood, it was determined that the average moisture content of all four gluing variants was $10 \pm 1\%$. The plywood pressing temperature used in the study was 135 C - slightly lower than that used in the production of 160 C for PF resin adhesive (Thoemen, Irle & Sernek, 2010). It also means that the energy capacity for the production of 1 m³ of plywood would be lower. However, it is higher than if urea formaldehyde (UF) or MF (melamine formaldehyde) resin adhesive would have been

used, according to the pressing temperature of 100 to 120 C reported in the research literature (Thoemen, Irle & Sernek, 2010).

The adhesive consumption used in the study also does not contradict the lower and average limits set by the adhesive manufacturer, as well as the limits of 160 to 230 g m⁻² reported in other studies (Zeppenfeld & Grunwald, 2005). In the production of one cubic meter of plywood, the consumption of adhesive can be up to 20% (Volynskii, 2003). Even if the data showed a significant improvement in mechanical properties by increasing the consumption of adhesive, manufacturers would hardly be willing to increase the cost of the product and the final price of the product, as this is not economically justified.

As a result of the study, the real thickness of each plywood group after hot pressing was also determined (Figure 2).

Figure 2. Thickness of plywood by gluing group.

Due to the various factors mentioned above, plywood actual thickness may vary; therefore, the permissible tolerances for the respective plywood thickness have been determined. According to the European standard LVS EN 315 (2000) – the lower and upper tolerances limit of 9 mm thick plywood (7 veneers, moisture content $10 \pm 2\%$) is 8.3 and 9.5 mm, respectively. According to the manuals of JSC 'Latvijas Finieris' and Finnish plywood handbook, the upper and lower tolerance limit is 9.5 and 8.8 mm, respectively (Finnish forest industries federation, 2002; Latvijas Finieris, 2020). The lower tolerance limit has by 0.5 mm stricter compared to requirements of the European standard LVS EN 315 (2000).

The plywood gluing group HIGHEST had the highest increase in thickness of 9.6 ± 0.1 mm (Figure 2), which is 0.1 mm more than the maximum permissible limit according to requirements of LVS EN 315 (2000) standard. The lowest thickness was 8.8 ± 0.1 mm for the plywood gluing group LOWEST. Pressing degree 12% for HIGHEST and 18% for LOWEST plywood group were determined. Study results show that if higher density veneers in all plywood plies are used, they compressed less; therefore, more attention should

be paid to the upper limit of thickness tolerance in order to meet the requirements of the standards LVS EN 315 (2000).

As a result of the study, it was found that the pressing degree of plywood directly depends on the density of veneers and, the highest, it is for plywood, in the lay-up scheme of which all veneers have a lower density ($502\text{--}540 \text{ kg m}^{-3}$), reaching 17%. If the outer plies of plywood have veneers with a lower density ($544\text{--}599 \text{ kg m}^{-3}$) and the inner plies have a higher density ($613\text{--}636 \text{ kg m}^{-3}$), or vice versa - the outer plies have a higher density ($616\text{--}626 \text{ kg m}^{-3}$) and inner plies lower density ($560\text{--}582 \text{ kg m}^{-3}$), the compression degree is lower or 14%. Compression degree is the lowest if all veneer plies have higher density veneers ($644\text{--}690 \text{ kg m}^{-3}$) or 11%.

The obtained study results do not differ significantly from the pressing degree of plywood used in production by 15% and also by the data found in the technical literature by 12% (Volynskii, 2003).

Determination of bending properties and gluing quality

Figure 3 shows the strength of static bending in the parallel and perpendicular direction of the plywood, depending on the densities of the veneers used, as well as the scheme of the veneer lay-up in the plywood.

Figure 3. Bending strength in accordance with standard LVS EN 310.

As shown in the figure 3, the direct effect of density on the bending strength is greater in the parallel direction of the fibers in plywood. No significant density effect was observed perpendicular to the fibers. The highest static bending strength of $101.9 \pm 6.6 \text{ N mm}^{-2}$ parallel to the fibers was observed in the plywood group HIGHEST, which does not differ significantly from the static bending strength of $99.3 \pm 3.4 \text{ N mm}^{-2}$ observed in the plywood group HIGHER. The value of $p > 0.05$ obtained using the ANOVA t -test shows that the difference between the bending strength average values of the above mentioned investigated plywood groups is not significantly different.

As it was in this study, also the studies conducted by other authors on the use of tree species of different densities in plywood concluded that the higher the wood density, the higher the mechanical properties of the final product. It was reported in Kallakas and colleagues' study on the suitability of birch, black alder, white alder and aspen for plywood manufacturing (Kallakas *et al.*, 2020).

The lowest bending strength parallel to the fibers $69.9 \pm 9.9 \text{ N mm}^{-2}$ was determined by plywood group LOWER. The difference between the highest and lowest strength in static bending parallel to the fibers is 32 N mm^{-2} . The value of $p < 0.05$ obtained using the ANOVA t -test shows that the

difference between the bending strength average values of the above mentioned investigated plywood groups is significantly different.

For LOWER plywood gluing group, the strength in static bending parallel to the fibers is 11 N mm^{-2} lower than for plywood gluing group HIGHER. Using the ANOVA t test, the p -value is < 0.05 , and the observed difference between the selected sample means is sufficiently conclusive to suggest that the mean bending strength for this plywood gluing group would differ significantly.

The strength in static bending perpendicular to the fibers in all plywood gluing groups were very similar in the range from $58.7 \pm 5.0 \text{ N mm}^{-2}$ for the plywood group LOWEST, up to $64.2 \pm 3.5 \text{ N mm}^{-2}$ for plywood group HIGHEST. The difference between the highest and lowest strength in static bending perpendicular to the fibers is 5.5 N mm^{-2} . Using the t test, the p -value in all four plywood gluing groups is < 0.05 , and the observed difference between the selected sample means is sufficiently convincing to state that the average bending strength for these plywood gluing groups would differ significantly. Similar tendencies appear when analysing the values of the modulus of elasticity of the same samples groups (Figure 4).

Figure 4. Modulus of Elasticity in accordance with standard LVS EN 310.

The highest modulus of elasticity in bending parallel to the fibers is $12707 \pm 812 \text{ N mm}^{-2}$, which is for plywood gluing group HIGHEST, the lowest modulus of elasticity in bending parallel to the fibers is $7946 \pm 690 \text{ N mm}^{-2}$, which is for plywood gluing group LOWEST. The difference between the highest and lowest modulus of elasticity parallel to the fibers is 4761 N mm^{-2} .

For the gluing group LOWER, the modulus of elasticity in bending parallel to the fibers is 1430 N mm^{-2} lower than for plywood gluing group HIGHER.

It can be observed that the modulus of elasticity in bending perpendicular to the fibers in all gluing groups is very similar in the range from $4712 \pm 183 \text{ N mm}^{-2}$ for the plywood group LOWEST, to 5542 N mm^{-2} for the plywood group HIGHER. The difference between the highest and lowest modulus of elasticity perpendicular to the fibers is 830 N mm^{-2} .

It can be observed that the density of plywood groups:

HIGHER and LOWER are 685 and 688 kg m^{-3} , respectively, and they do not differ significantly.

On the other hand, for plywood group HIGHEST the average density is 777 kg m^{-3} , and for plywood group LOWEST the average density is 605 kg m^{-3} , and they differ significantly. Studies by other scientists on the use of different wood species in plywood have concluded that using lower density wood species veneers provide lower strength than using only higher density wood species veneers (Kallakas *et al.*, 2020).

The quality of gluing for manufacturers of plywood is described according to the requirements of the standard LVS EN 314-1 (2005) - both tensile shear strength and wood failure, describing each of the pre-treatment types of plywood resistance. The results of the study are summarized in Table 2.

Table 2

Gluing quality in accordance with the requirements of standard LVS EN 314- 2 (2000)

Plywood gluing group	Gluing quality/ standard deviation, N mm ⁻²			Wood failure, %		
	2 nd ply	4 th ply	6 th ply	2 nd ply	4 th ply	6 th ply
immersion for 24 hours in water at (20 ± 3) °C						
LOWEST	1.28/0.13	1.10/0.14	1.25/0.21	90	85	95
HIGHEST	2.05/0.21	1.76/0.15	1.96/0.11	100	100	100
LOWER	1.35/0.15	1.78/0.11	1.36/0.11	95	100	95
HIGHER	1.89/0.10	1.21/0.16	1.88/0.13	100	90	100
immersion for 4 hours in boiling water, then drying in the ventilated drying oven for 16 hours at (60 ± 3) °C, then immersion in boiling water for 4 hours, followed by cooling in water at (20 ± 3) °C for 1 hour						
LOWEST	0.83/0.19	0.70/0.14	0.78/0.21	55	50	55
HIGHEST	1.65/0.21	1.36/0.15	1.56/0.11	80	70	80
LOWER	0.95/0.15	1.49/0.10	0.94/0.12	60	75	60
HIGHER	1.49/0.10	0.90/0.15	1.48/0.13	70	60	70
immersion for 72 hours in boiling water, followed by cooling in water at (20 ± 3) °C for 1 hour						
LOWEST	0.65/0.12	0.52/0.16	0.55/0.09	45	40	45
HIGHEST	1.16/0.18	0.96/0.15	1.16/0.11	60	50	60
LOWER	0.55/0.15	1.09/0.10	0.54/0.12	45	55	45
HIGHER	1.09/0.10	0.50/0.15	1.08/0.13	55	45	55

A study by Kallakas *et al.* (Kallakas *et al.*, 2020) also found that if the density of the raw material is lower, then when manufacturing plywood, the density of plywood increases, or it is more likely that lower-density wood veneers will compress more. This must be taken into account when choosing veneer thickness for lower density veneers when plywood is manufactured.

The plywood group HIGHER had the same thickness as plywood group LOWER. The pressing degree did not differ for these plywood gluing groups - and no significant effect of the density, if in outer plies are higher density and inner plies lower density veneers or vice versa, on the pressing degree was not observed.

The mechanical properties of plywood can be provided by a combination of different wood species used in plywood construction, such as birch and alder wood veneers (Kallakas *et al.* 2020). This study concludes that decreasing wood

density increases adhesive consumption (Kallakas *et al.* 2020). In other studies that have been carried out, the authors recommend that the density of wood should be taken into account in the production of glued wood products when changing raw materials (Iejavs *et al.*, 2021). As plywood is also glued using veneers with different properties, this should be taken into account when making plywood. Although the high density of birch wood does not allow for significant densification of veneers, as a possible solution to reduce adhesive consumption up to 25% and also pressing pressure up to 22% (Bekhta & Marutzky, 2007), it could be the objective for the next research regarding possibilities of densification of the birch veneers.

It is a well-known fact that the densification of veneers and higher consumption of adhesive increase the density and mechanical properties of plywood (Cristescu *et al.*, 2015; Rautkari *et al.*, 2015).

Veneer densification process increases the density of the veneer only at their initial processing stage. If other technological processing processes do not follow the initial veneer densification, properties at the plywood manufacturing process and also during plywood exploitation decreases.

Therefore, in order to achieve a permanent initial densification effect of veneers, thermomechanical densification must be performed, as a result of which the surface roughness of veneers is also reduced (Bekhta *et al.*, 2014).

By studying the literature data regarding the results of this study, high performance density sorting technological solutions should be introduced in the manufacturing of plywood, as this could be certainly not possible by manual operation due to high speed of veneer movement. The introduction of new automated technologies in the production of plywood can reduce the area of staff and technology deployment, sometimes up to 42%, increase the quality of the final product (Regattieri & Bellomi, 2009). This could also apply to density sorting machines if veneer manufacturers decide to put on such equipment. As a result of this study, it was concluded that veneers should be classified into at least two groups – lower and higher density. This means that for sorting veneers not only by quality, but also by density, the area occupied by warehouses must be at least twice as large.

The plywood constructive solution, especially its thickness, requires special attention compared to such materials as wood Honeycomb panels, whose density does not affect the stability of the shape (Spulle *et al.*, 2018). The density of plywood directly affects both the mechanical properties and the possible swelling especially in its thickness. This factor should be taken into consideration if lower or higher density veneers have been used. This subject could be reason for the further research. Thus, if it is necessary to increase the mechanical bending properties of plywood in the grain direction, as well as to ensure the highest gluing quality, all veneers which are used in the plywood lay-up scheme should have the highest possible density. Veneer density sorting in the manufacturing process, if moisture content of the veneers does not differ significantly, could be done by determining the mass of each veneer. In production, each veneer volume differs and this fact should be taken into account. In production, the easiest way could be to use the scanning methods and systems which nowadays are very accurate; also, they could be used for the measurements of volume.

The results of the study will allow birch plywood manufacturers involved in direct production sort veneers by density, in order to produce plywood with very predictable gluing quality, plywood thickness and mechanical properties in bending.

Conclusions

1. Plywood in which all the plies of veneer had a higher density (from 644 to 690 kg m⁻³) plywood group HIGEST, had a maximum thickness of 9.6 mm, which is 0.1 mm more than the maximum permissible limit (LVS EN 315, 2000), the lowest thickness was 8.8 mm for plywood made of lower density veneers (502 to 540 kg m⁻³) in all the plies and the pressing degrees in both groups were 12% and 18%, respectively.

2. The highest strength in static bending of 101.9 ± 6.6 N mm⁻² is found for 7- ply (9 mm thick) plywood (parallel to the

fibers) with a higher density (644 to 690 kg m⁻³) in all plies – plywood group HIGHEST, which is significantly higher than for plywood with a lower density (502 to 540 kg m⁻³) in all plies – plywood group LOWEST, reaching strength of static bending of 69.9 ± 9.9 N mm⁻².

3. Plywood made of the highest density veneers (644 to 690 kg m⁻³) in all plies – plywood group HIGHEST has a static bending strength of 101.9 ± 6.6 N mm⁻², and it does not differ significantly from the average static bending strength of 99.3 ± 3.4 N mm⁻² - for plywood whose inner three plies of veneer have a lower density (560 to 582 kg m⁻³) and the outer two plies have a higher density (616 to 626 kg m⁻³) – plywood group HIGHER.

4. The bending strength perpendicular to the fibers for all plywood gluing groups is very similar in the range from 58.7 ± 5.0 N mm⁻², for plywood group LOWEST, up to 64.2 ± 3.5 N mm⁻², for plywood group HIGHEST, and the difference is not statistically significant.

5. In order to obtain similar strength in static bending, especially for plywoods with special laying-up schemes or traditionally outer veneer fiber direction matching, it is not necessary to use the high density veneers (after sorting is done) throughout the thickness of the plywood, it is sufficient if the two are in the outer plies, thus promoting the sustainable use of wood.

6. Density also affects the gluing quality: after immersion for 24 hours in water (20 ± 3) °C, all standard requirements are met, even after immersion for 4 hours in boiling water, and then dried at (60 ± 3) °C for 16 hours, followed by immersion for 4 hours in boiling water and cooled at (20 ± 3) °C for 1 hour the strength decreases of about 10% to 20% wood failure was reached. The greatest drop in properties was achieved by immersing plywood for 72 hours in boiling water and then cooling in water (20 ± 3) °C for 1 hour: by 30% with a higher density veneers, and by even 50% with a lower density veneers.

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Acknowledgments

This research was carried out within the project G2 “Prediction of Properties of the Environment Friendly Engineered Wood Composites” (No. 3.2-10/2) co-financed by the program “Implementation of fundamental research at Latvia University of Life Sciences and Technologies”.