ONLINE ISSN 2069-7430
ISSN-L 1841-4737
PRO LIGNO
www.proligno.ro
Vol. 19 N° 4 2023
pp. 78-90

HIGHLY DENSIFIED LAMINATED COMPOSITES WITH PRE-COMPRESSED VENEERS

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Abstract:

The objective of this study is to evaluate the physical and mechanical properties of highly compressed beech veneers (compression rate up to 40%) used for the manufacture of laminated products with high density. Dimensional stability, elastic properties, Brinell hardness and the quality of bonding were tested. Conventional (PVAc, MUF and PUR) and alternative adhesives (based on casein) were used for the bonding of 7-layered laminated veneer-based high-density products. Based on the results of the study, a compression rate of 40 % was reached for all composites. Tensile shear strength of all panels was from 1.3 up to 3.3-fold higher than that of control (pagholz, as an industrial product) and modulus of elasticity exhibited higher values in the case of using polyurethane and melamine urea-formaldehyde. Thickness swelling and water absorption after 24 hours, bending strength and Brinell hardness should be improved by changing pressing and processing parameters. The spring-back effect was the lowest (7%) and the highest (14%) for the compressed veneers with MUF, respective casein adhesive application. Casein-based adhesive application for laminated veneer products (LVP) is an alternative for a completely recyclable and sustainable product. These LVP can be applied in buildings as wear layers between beams or in contact with other materials (concrete). Their use reduces the cross-section of the element, increases safety during use and significantly reduces the consumption of raw materials, extends the products service life and ensures a higher resistance to climatic factors compared to solid wood (i.e. GLT, CLT, SWP).

Key words*: densified laminated veneer products, compressed beech veneers, spring-back effect, casein-based adhesive.*

INTRODUCTION

Wood is a structural and environmentally friendly low weight building material with high strength and specific stiffness (Kollmann and Côté 1984). As naturally grown material, wood shows high variation in mechanical properties due to growth conditions as soil type, nutrients, climate and specific characteristics as the presence of knots, cracks, grain-angle (Kretschmann 2010). To overcome these challenges, engineered wood products (EWP) were constantly being developed and improved for structural applications (Sotayo et al. 2020). These products are a result of adhesive bonding of wood lamellae, veneers, wood chips, particles etc. to form larger panels or beams (Harris and van de Kuilen 2016). In structural applications, where higher mechanical properties are desired, wood densification is a technique commonly used to increase the density of the products with high porosity structure by decreasing the thickness by compression (i.e. pressing) of raw

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material (Saari et al. 2015). This procedure is not new, it has been applied since more than a century. Patents subjecting mechanical compression of wood were issued by Sears in 1900, Walch and Watts in 1923, Oleheimer in 1929, Brossmannes in 1931, Esselen in 1934 and Olson in 1934 (Kollmann and Côté 1968-1975). Compressed wood was produced since more than eight decades under different trade names as Lignostone, Lignifol, Staypak, Compreg or Panzerholz (Fang et al. 2012). Wood compression determines a reduction in the voids between cells and cell lumen. During compression under steam (moisture and heat), the wooden cell structure is lastingly modified. The number and type of collapsed cells are the main factors influencing mechanical and physical properties of compressed wood (Arruda and Del Menezzi 2016). By compression, some cell structures are modified and void volume of wood is reduced, resulting a smooth surface and better thermal conductivity of material (Candan et al. 2010). The compression techniques are not applied only on solid wood, but also on veneers, lamellae and wood chips (Saari et al. 2020). During compaction, the cell structure is modified. The higher the degree of compaction of each veneer, the greater the change in mechanical and physical properties. Cell collapse is deliberately induced by the cell walls bending or even breaking. The degree of compaction depends on the annual ring position of the veneers, moisture content and the compaction parameters at the hot press (time, temperature and pressure). Compression properties depend mostly on various anatomical features of the wood specimen such as density, the percentage of late wood material, ray volume and loading direction (Kutnar and Šernek 2007). However, this type of compressed wood is unstable and recovers its initial shape almost completely when subjected to moisture and heat (Fang et al. 2012). Spring-back of compressed wood is the main negative consequence of compression and is caused by the elastic deformation energy storage during the compression of semi-crystalline microfibrils and hemicelluloses (Arruda and Del Menezzi 2016). Compressed veneers were made out of beech (*Fagus sylvatica)* (Cristescu et al. 2015), Japanese cedar (*Cryptomeria japonica*) (Shams et al. 2004) or radiata pine (*Pinus radiata)* (Xu et al. 2009).

Densification techniques using physical or mechanical compression and chemical impregnation or a combination of these methods are usually applied. Chemical impregnation of the cell lumina with fluid substance proved to be expensive and with undesirable effects on the native characteristics and sustainable properties of wood (Navi and Heger 2004). To improve dimensional stability, compression mingled with steam and heat gained more and more interest (Fang et al. 2012).

The binders used for the manufacture of EWP are designed to form a water or at least moisture resistant bond between the wood materials by connecting the surfaces, holding the materials together (Fay 2021). This is the result of the attraction forces that emerge from chemical bond, physical interaction or mechanical connection between wood and binder. In terms of sustainability, recyclability and environmental impact there are continuous concerns regarding adhesives (mostly formaldehyde-based) and metal fasteners (Sotayo et al. 2020). Many adhesives include in their formulation formaldehyde (e.g. urea-formaldehyde), which is considered harmful for the environment due to discharging of toxic gases (volatile organic compounds - VOC) (Tudor et al. 2020). Admitting that the cured adhesives are roughly safe, under certain conditions and changes in relative humidity of SWP, formaldehyde gas is discharged (Mantanis et al. 2018). Formaldehyde is air pollutant and carcinogen to humans (Frihart and Hunt 2010), (Barbu et al. 2020) but its emissions can be diminished by using additives (fillers) based on tree bark powder (Réh et al. 2021). To overcome such hazards, regulatory standards limit the use of such adhesive and establish maximal levels of emissions of formaldehyde and VOC during production and in finished wood products (Frihart and Hunt 2010).

An alternative to these conventional adhesives is casein. Casein has been used as an adhesive in Europe since the beginning of the 20th century (Petrović et al. 2017). Casein is a protein that belongs to the group of organic compounds and is obtained from skimmed milk (Adams 2021). Casein-based adhesives are heat-resistant, weatherproof and represent a viable alternative to the conventional adhesives (Schwarzenbrunner et al. 2020).

Replacing metal fasteners with hardwood dowels was introduced since more than 30 years in the wood industry (González Fueyo et al. 2009). Combining solid wood and hardwood dowels in EWP (manufactured without metal fasteners) leads to improvement of recyclability and reducing environmental footprint of these products (Hwang and Komatsu 2002). Recent studies revealed that compressed wood or veneer can be used as alternative to metallic fasteners and synthetic adhesives, in timber-to-timber connections and EWP, but with limited use due to sparse data about their mechanical properties (El-Houjeyri et al. 2019).

The aim of this paper is to analyse the compression rate, spring-back effect and to scrutinize the influence of conventional (polyvinyl acetate, polyurethane, melamine urea formaldehyde) and protein-based adhesives (casein) on the bonding quality and the mechanical and physical properties of 7-layered beech highly densified veneers laminated product. The recyclability of the product plays a major role in this study, as the casein-pressed veneers can be reused or re-valorised without any special treatment.

MATERIALS AND METHODS

Beech veneers (*Fagus sylvatica*) with dimensions 1 m x 1 m, thickness 1 mm, were "ironed", to reduce the wavy natural aspect of plys and to pre-compress them from 1 mm to 0.9 mm, were provided by Kirchgasser Furniere GmbH (Grödig, Austria). The veneers were cut to size with a circular saw to 750 x 150 mm longitudinal stripes. Four types of adhesives were used for the bonding of the compacted beech veneers: polyvinyl acetate (PVAc) type GXL 3 from Rakoll (St. Paul, USA), melamine-urea formaldehyde (MUF) type 1247 from Akzo Nobel (Elixhausen, Austria), polyurethane (PUR) type 505 from Kleiberit Co. (Weingarten, Germany) and casein powder, type 63200 from Kremer Pigmente (Aichstetten, Germany). For the production of casein-based glue were mixed marble pit lime (stored for three months and composed of white hydrated lime, solid content 40%) from Baumit Co. (Wopfing, Austria), water glass (sodium silicate) from Wöllner (Ludwigshafen am Rhein, Germany) and tap water (20°C, pH-value 7). The casein based adhesive formulation builds on (Schwarzenbrunner et al. 2020).

Control board (45 cm x 45 cm x 4 mm, 7 layered) from Pagholz Co. (Loitz, Germany) made of parallel laminated beech veneers soaked in/with phenol-formaldehyde (PF) resin bath, hot pressed at 135-155°C to over 1,250 kg/m³ was used as a benchmark. Mechanical and physical performances of it range in the values of other similar products, i.e. Delignit (Blomberg Holzindustrie Co., Blomberg, Germany) and Dehonit (Deutsche Holzveredelung Co., Kirchhundem, Germany) as follows: density ~ 1,350 kg/m³, bending strength ~ 165 N/mm², modulus of elasticity ~ 16,500 N/mm², tensile shear strength ~ 1.6 N/mm², water up take ~ 3% etc.

Pre-compression of the beech veneers

The beech veneers achieved 8 % moisture content after conditioning at 22.5°C and 63.2 % relative humidity, these parameters were chosen to guarantee the comparability of after testing the properties of the panels made of the pressed beech veneer. Afterwards the veneers were pre-compacted in a hydraulic laboratory press Höfer HLOP 280 (Taiskirchen, Austria) at a temperature of 180°C, a pressing time of 8 min and a pressure of 25 N/mm² (Fig. 1, left). After pre-compaction, the veneers were cooled down at room temperature (22°C) without pressure and used for the manufacture the 7-ply LVP. After pre-compaction, veneer thicknesses were measured in 5 points of each ply, to calculate the compaction degree (in %) (Equation 1). The spring back effect was calculated at intervals of 2, 5, 7 and 24 hours (Equation 2), by measuring the thickness of the hot pre-compacted veneers and the thickness of the cooled down veneer strips.

Adhesive application on the pre-compacted beech veneers

At first were performed pre-tests on veneer bonding, to establish the proper adhesive amount for each type of veneer, as follows:

1) The densified veneers were soaked in adhesive bath for 10 s. Afterwards, the excess adhesive was removed;
2) The adhesive was applied onto one side of every ply on the entire surface.

For both bonding trials, the adhesive amount was 130 g/m².

It resulted that for the given laboratory conditions the method 2) (Fig. 1, right) is more appropriate to be used for adhesive application.

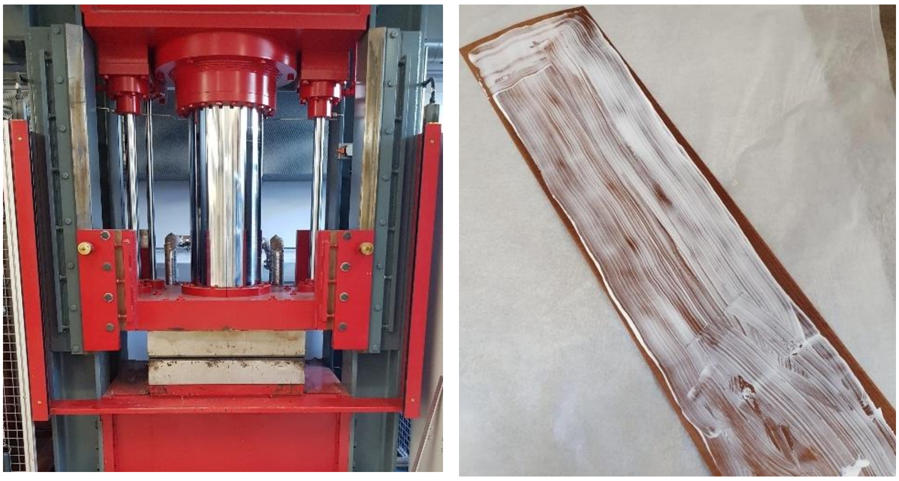

Fig. 1.
Hydraulic press Höfer HLOP 280 at FH Salzburg, Campus Kuchl for pre-compaction and panel pressing (left); beech veneer at least 35% compacted (from 1 to/0.6 mm thickness) with PVAc application (right).

A notched trowel was used to spread the adhesive on veneer face, afterwards the veneer sheets (750 x 150 mm) were assembled parallel to each other to form 7-layered LVP, using hydraulic hot press Höfer HLOP 280 (Table 1). In the case of casein adhesive were applied 140 g/m² and 150 g/m² because this formulation exhibits higher viscosity compared to all other adhesives used with a uniform surface gluing. The press temperatures for each type of adhesive were chosen based on pre-tests. The resins softened the cell wall of the wood and thus it occurred a non-destructive collapse during the pressing process. Also the press time was selected in accordance with pre-tests. For casein-based adhesives was chosen a lower press pressure and increased press time because it takes longer for the resin to cure and harden. The press temperature was considerably lower for the veneers glued with MUF adhesive, but the press time was considerable increased to 30 minutes.

Table 1

Press parameters and adhesive amount for different 7-ply LVP made of pre-compacted (~40%) beech veneer

panel no.	**adhesive type**	**press temperature [°C]**	**press time [min]**	**press pressure [N/mm²]**	**adhesive amount [g/m²]**
1	PVAc	65	30	5	130
2	PVAc	65	30	25	130
3	MUF	85	30	5	130
4	MUF	85	30	25	130
5	PUR	55	30	5	120
6	PUR	55	30	25	120
7	Casein	50	50	19	150
8	Casein	50	60	19	140

After hot pressing, the thickness of each panel was measured (Fig. 2), to determine compaction rate (CR) (Equation 1) and the spring back effect (SB_{effect}) (Equation 2), the latter observed by measuring the thickness of the panels (hot, after pressing and cold, after cooling) at different time intervals (2, 5, 7 and 24 h).

Fig. 2.
Measuring the thickness of 150 x 750 mm pre-compacted beech veneer.

The compression ratio CR (%) was calculated with Equation (1)

$$CR = \frac{T_{v1} - T_{v2}}{T_{v1}} \ x \ 100 \ (\%) \qquad (1)$$

where: T_{v1} and T_{v2} represent the veneer thickness prior and after hot pre-pressing (mm). The measurements for T_{v2} were made 60 min after the pre-pressing process.

After pressing, the 7-layered LVP(LVP) were conditioned at 20°C and 65% relative air humidity, until constant mass was achieved.

The spring-back-effect (SB_{effect}) was calculated with Equation (2)

$$SB_{effect}\ [\%] = \frac{pt_c - pt_h}{pt_h} x100\ (\%) \qquad (2)$$

where: pt_c - thickness of cooled down LVP and pt_h – thickness of hot LVP (mm).

The laminated veneer panels were trimmed at first and then the samples were labelled for each specific test (Fig. 3). Each board was manufactured with five replications for each set of adhesive (PVAc, MUF, PUR and casein-based).

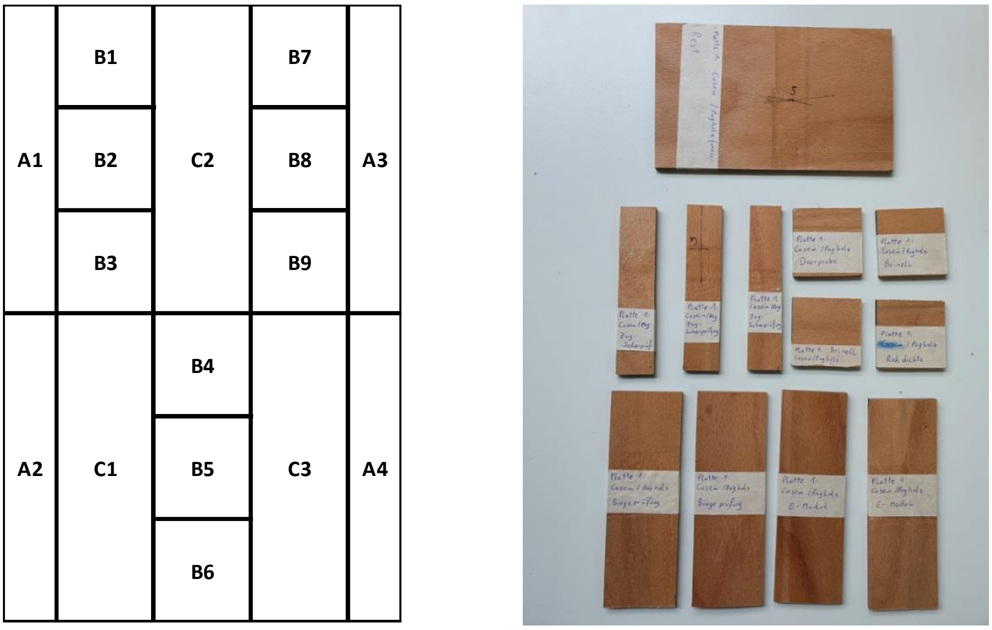

Fig. 3.
Cutting plan of the test samples (left) and labelled test specimens (right).

In Fig. 3 (left) each letter represents a type of test, such as "A" for bending strength, "B" for thickness swelling and water absorption and "C" for the tensile shear strength and Brinell hardness. The samples were cut considering minimal material waste generation and were taken from different parts of the panel, to ensure a representative scatter of results, eliminating spots with defects.

Prior to testing, the samples were stored in a climate chamber, at 20°C and 65 % relative air humidity of until constant mass was achieved.

The mechanical tests were performed with universal testing machine Zwickl/Roell Z250 (Ulm, Germany) with Master testing software as follows: modulus of rupture and modulus of elasticity, according to EN 310:2005, tensile shear strength, according to EN 314-1:2004 and Brinell hardness, according to EN 1534:2000. Thickness swelling and water absorption were determined according to DIN 52183:1977and the density in harmony with DIN 52182:1976.

The results of LVP were compared with the industrial product of the Pagholz Co. (Loitz, Germany). The industrial panel was tested with the LVP specimens and is indicated in the graphs as control sample.

RESULTS AND DISCUSSION

This section presents at first the values for compression rates of densified veneers together with spring-back effect of LVP and hereafter physical and mechanical properties of the 7-ply LVP.

Compression rate and spring-back effect

The initial thickness of veneers was 0.9 to 1 mm. Afterwards all veneers were pre-compacted (pressing time 8 min, press pressure 25 N/mm² and press temperature of 180°C). After pre-pressing, the average thickness of compacted veneers was 0.55 mm.

A minimum compression rate of 35% on average was achieved for all veneers, with average compression rates ranging from 35.89% (Set 8) to a maximum of 40.37% (Set 4). The pre-compacted veneers (Set 1 to Set 8) were pressed with PVAc (Board 1 and 2), MUF (Board 3 and 4), PUR (Board 5 and 6) and casein (Board 7 and 8) (Fig. 4).

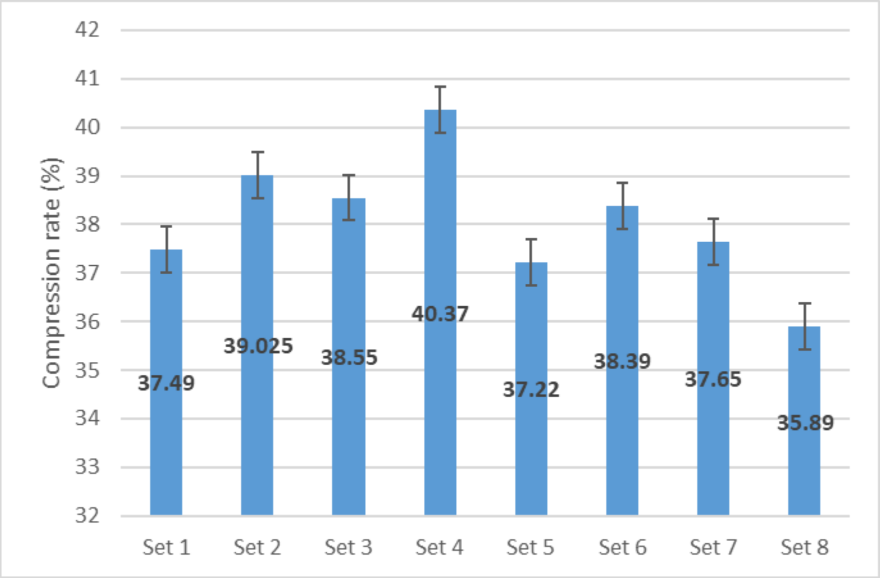

Fig. 4.
Average compression rate (%) of compressed veneers (n=25): PVAc: Board 1 and 2, MUF: Board 3 and 4, PUR: Board 5 and 6, Casein: Board 7 and 8.

The spring back effect has a significant impact on the final panel thickness, because all LVPwere hot pressed (Table 1), but after cooling down for 2, 5, 7 or 24 hours, the thickness of veneer composite increased significantly (Table 2). The shape memory effect is a prevalent aspect of smart materials, that are able to save a transitory shape received as a result of deformation under certain conditions. But the testing specimen remembers its earlier shape and there is a potential to return completely or partial to its initial shape. Spring-back is a natural reaction of the wood to the release stresses imposed during pressing. The difference between the memory effect and the spring-back is that spring-back occurs immediately as soon as the stress causing the deformation is eliminated, thus, the sample shows an immediate set-recovery (Báder and Németh 2020). It has also been previously found that higher compression ratio leads to greater immediate spring back due to higher inner stresses created during compression (Laine et al. 2016).

Table 2

Spring back effect of the LVP (n=4) at different cooling times (2, 5, 7 and 24 h)

Group	**SB2***	**SB5***	**SB7***	**SB24***
PVAc	3.31	6.95	9.6	9.93
PUR	2.84	3.78	5.91	7.09
MUF	5.74	6.98	7.48	7.73
Casein	4.83	7.39	12.2	14.2

*SB2, SB5, SB7 and SB24 the spring back effect after 2, 5, 7 and 24 h.

The ***spring*** back effect ***shows*** the difference in thickness between the panels measured directly after hot pressing and at different intervals of cooling. After 24 hours, the panel bonded with PVAc had a spring back of 9.93%. The board bonded with PUR achieved 7.09%, the board bounded with MUF 7.73% and the board glued with casein 14.2% after 24 h. The change in thickness was perceived to be by far the highest for the panel bonded with casein.

The panel glued with PUR had the lowest spring back and therefore it can be stated that the use of PUR adhesive led to a lesser tensile laminated product.

Density of 7 - layers LVP

The density of all LVPwas significantly lower compared to Control (Fig. 5). The lowest values were determined for the group bonded with formulation Casein 1 – Board 7 (up to 1100 kg/m³), followed by the samples of Board 3, bounded with MUF (adhesive application up to 1160 kg/m³). Higher densities, but still under 1300 kg/m³ were obtained for the Boards 1 and 2 (bound with PVAc). The increase of press pressure from 5 N/mm² to 25 N/mm² influences positively only the boards bonded with MUF and determine a homogenous scattering of density values of the 7-layered composite bonded with PUR.

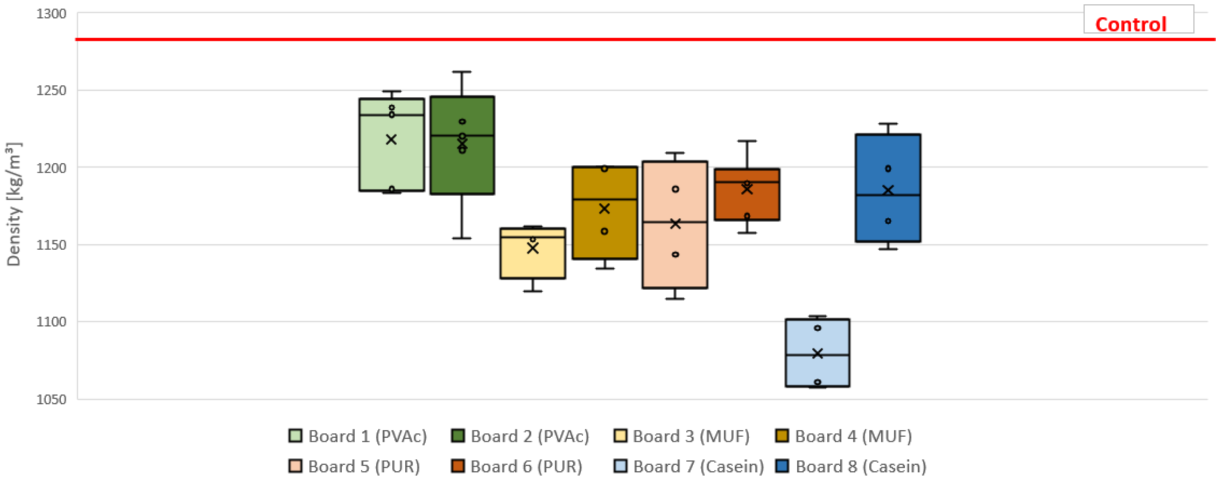

Fig. 5.
Density (kg/m^3) of the 7-ply pre-compacted beech veneer LVP.

Thickness swelling after 24 hours

The testing specimens of Board 5 (PUR) showed the lowest thickness swelling (TS) from all manufactured veneer composites, with values ranging from 23 to 28% (Fig. 6). With a difference of 30.9% between the maximum and minimum values, the samples of the Board 3 (MUF) showed the most increased swelling in thickness, with the maximal scatter (standard deviation of 12.9%). It is interesting how the LVPbound with MUF exhibited such differences in terms of average values and also standard deviation. It can be presupposed that during the application of adhesive without hardener the Board 3 was subjected to hydrolysis in a different manner compared to Board 4. These MUF-bonded joints are assumed applicable for structures when weathering and water exposure is limited (Wimmer et al. 2013). For the LVPbound with casein group was measured an average thickness swelling of 31.2%, discrete lesser than the TS of the boards bonded with PVAc (Board 1: 28.8%; Board 2: 32.6%) This is due to the specific properties of the adhesive, as it swells in combination with water (Fay 2021), (Ghahri et al. 2021). There is little information regarding the water-related properties of composites made of laminated compressed veneers, so the results can be confronted with the control sample that achieved the lowest TS that yielded from 3 to 12%. It cannot be drawn a tendency regarding press pressure or adhesive application between the groups. At 25 N/mm², the veneers bonded with PUR had the lowest scatter for TS, at values at least 3-fold higher compared to the control. In the case of casein-adhesive application, an increase of pressing pressure lead to decreased TS, that remained still significantly higher (from 24 to 35%).

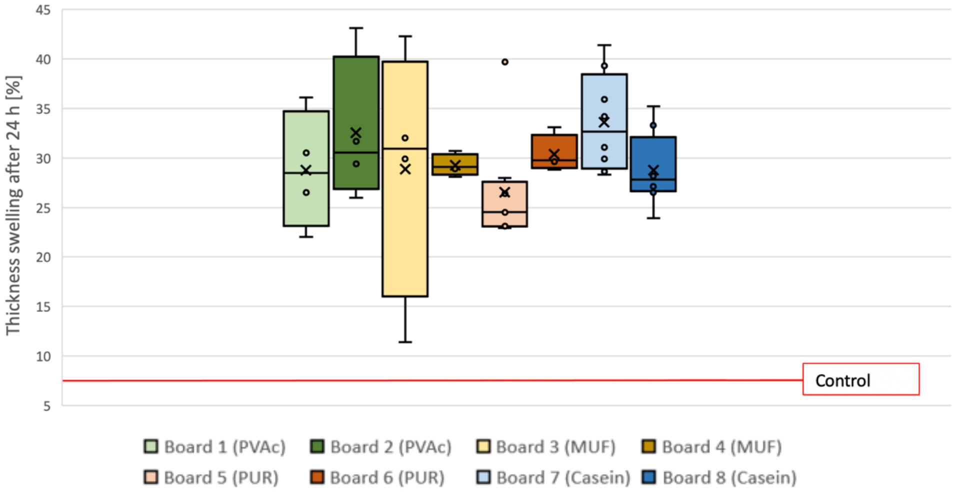

Fig. 6.
Thickness swelling after 24 h/TS (%) of the 7-ply pre-compacted beech veneer LVP.

Water absorption after 24 hours

The water absorption (WA) shows the strong influence of adhesive type on the water-related properties of the 7-layered beech veneer LVP (Fig. 7). The boards have an average water absorption of 32.7%. This value of WA is significantly higher than that of the average 6.3% measured for the control samples. The most constant behaviour was shown in the PUR group, with a standard deviation of 3.8% for the 12 samples.

The highest water absorption was measured for the Board 2 (PVAc), with an average value of 35.6%. For the Board 5 (PUR) was determined an average water absorption of 25.5% at a standard deviation of 3.5%. The WA of the LVP glued with casein is similar to the WA of the panes bound with PVAc, ranging from 20 to 50% WA. The behaviour of the LVP with casein-adhesive application is interesting, because the difference of 10 g/m² is reflected in board 8 in lower water absorption.

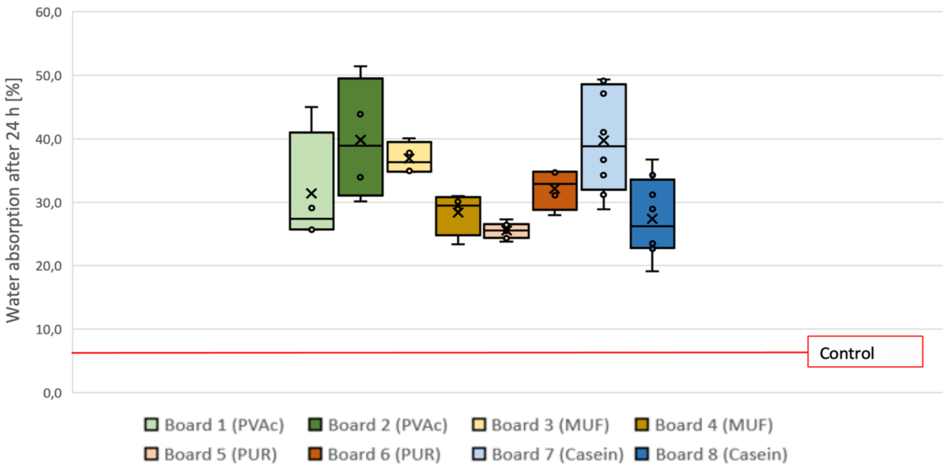

Fig. 7.
Water absorption after 24 h/WA (%) of the 7-ply pre-compacted beech veneer LVP.

Modulus of rupture and modulus of elasticity

All 13 testing specimens bonded with PUR (Board 5 and 6) showed the highest bending **strength** (modulus of rupture, MOR), included in the interval 200-240 N/mm² (Fig. 8). Their average flexural strength was 226 N/mm² (70 N/mm² standard deviation), which is with 45 N/mm² higher than the arithmetic mean ($\bar{x}$ = 181 N/mm²) of the samples bonded with casein adhesive, but the closest to the average value of 296 N/mm² reached by the control sample. A possible solution to increase the bending strength of the LVP produced with casein could be the use of a different adhesive formulation. For an adhesive amount of 130 g/m², the study of (Bekhta et al. 2009), that developed 5-ply plywood with compressed veneers, presented value for MOR from 130 to 150 N/mm² and for 140 g/m² the MOR was from 135 to 145 N/mm², so the findings of this study are consistent with (Bekhta et al. 2009), considering the increased number of veneer sheets and their orientation.

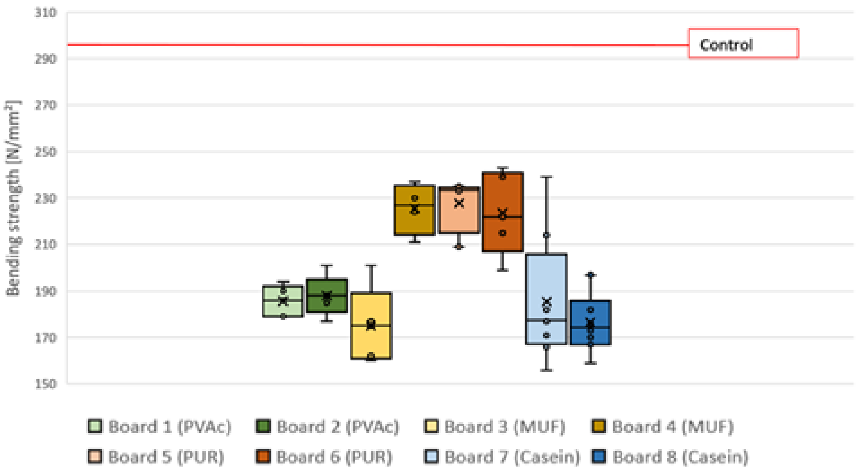

Fig. 8.
Bending strength/MOR (N/mm^2) of the 7-ply pre-compacted beech veneer LVP.

The highest values for the modulus of elasticity (MOE) (Fig. 9) were reached by all LVPbonded with PUR (Board 5 and 6) and by the Board 4 (MUF), with average values of 23,468 N/mm^2 (PUR); and 23,940 N/mm^2 (Board 4). An average modulus of elasticity of 23,940 N/mm^2 Board 4 (MUF) was determined for Board 4 (MUF), which is the highest mean value that exceeds with 1,852 N/mm^2 the MOE of control panel. With a difference of 10,721 N/mm^2 from the highest to the lowest test result, the Board 7 showed the highest standard deviation. For Board 8 (Casein) was calculated a standard deviation of 8,796 N/mm^2. It was assumed that due to the challenges encountered by adhesive application for panel production, the thickness of adhesive joint is not constant, resulting in such scatter of test results. As density influences all mechanical properties, it is interesting to observe that the PVAc-bonded boards with highest density did not reach the highest MOR and MOE. Mostly the PUR adhesive application positively influenced the bending strength and modulus of rupture, although the densities of PUR and MUF glued LVP are similar.

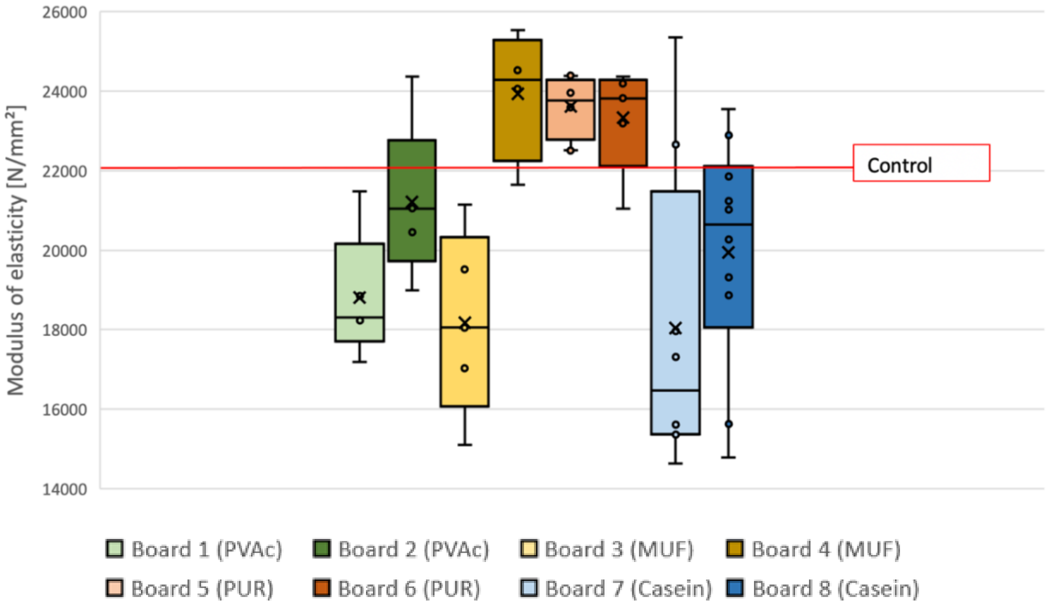

Fig. 9.
Modulus of elasticity/MOE (N/mm^2) of the 7-ply pre-compacted beech veneer LVP.

Tensile shear strength

By assessing the results of this test, the boards produced have an average tensile shear strength that is with 4.13 N/mm^2 higher than the value of the control sample (Fig. 10). The highest values of tensile shear strength (8.09 N/mm^2) were measured for the samples from Board 4 (MUF). The difference between the highest and the lowest value for the tensile shear strength for the samples of Board 4 (MUF) is 67%. A reduced scatter was observed for the samples sourced from the Boards 2, 3, 5, 6 and 8. For an adhesive application of 135 g/m^2, the study of (Bekhta et al. 2009) revealed values of tensile shear strength from 1.85 to 2.15 N/mm^2 for 5 ply composites with previously compressed veneer at a compression degree of 25%. Plywood (PY) with 7 plies pre-compressed veneers were scrutinized by (Bekhta and Salca, 2018). The results are contradictory with other studies as (Bekhta et al. 2012), (Bekhta and Marutzky 2007) and (Bekhta et al. 2018), that supported the theory that the shear strength of plywood with densified veneer was higher than that made of non-densified veneer. With increased number of densified veneers in the LVP the glued joint shear strength decrease significantly (Gaff et al. 2016). According to (Bekhta and Salca 2018), tensile shear strength for non-densified PY was with 5% higher than that of composite made with densified veneers (2.03 N/mm^2 and 1.92 N/mm^2 respectively). The shear strength of 5-ply PY with compressed veneers bonded with phenol-formaldehyde (PF 150 g/m^2) was analysed in the study of (Bekhta and Marutzky 2007), that calculated values from 2.36 to 2.86 N/mm^2.

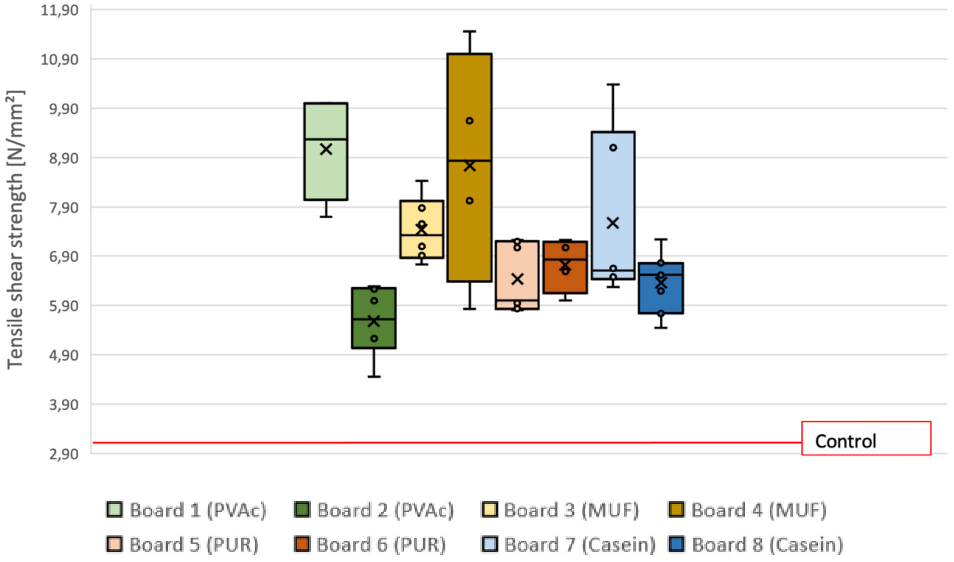

Fig. 10.
Tensile shear strength (N/mm^2) of the 7-ply pre-compacted beech veneer LVP.

Brinell hardness

The board with the highest density, with PVAc adhesive spread and 5 N/mm² press time did not reach the highest Brinell hardness (HB). (Fig. 11). It is also interesting how the groups with MUF and PUR adhesive spread, despite their relatively similar densities, reached different values for Brinell hardness. The lowest HB were achieved by the low-densified casein-bonded groups. For all testing specimens, HB values ranged from 35 to 87 N/mm², which are lower than the lowest hardness of the control group (about 90 N/mm²), that showed values higher with 66% compared to all groups. This increased HB of the reference (Control) is due to the PF resins, adhesive application (soaking of resin in veneers during and after bath in PF) and adhesive amount (also on both surfaces during PF bath) used for production of compressed veneers in high densified products (Zeppenfeld and Grunwald 2005). The samples from the board with PVAc adhesive application and pressed with 25 N/mm² showed the higher scatter with a difference of 32 N/mm² between the highest and the lowest test result. The research conducted by (Laine et al. 2016) stated that hardness can be significantly increased at a wood compression rate of 40 % (15-20 N/mm²) and can be even doubled by compressing 50% (up to 30 N/mm²). In the same study resulted that the indentation recovery of densified samples is mainly dependent on the compression ratio. The recovery increased due to densification up to a compression ratio 50% which doubled recovery compared to non-densified samples (Laine et al. 2016).

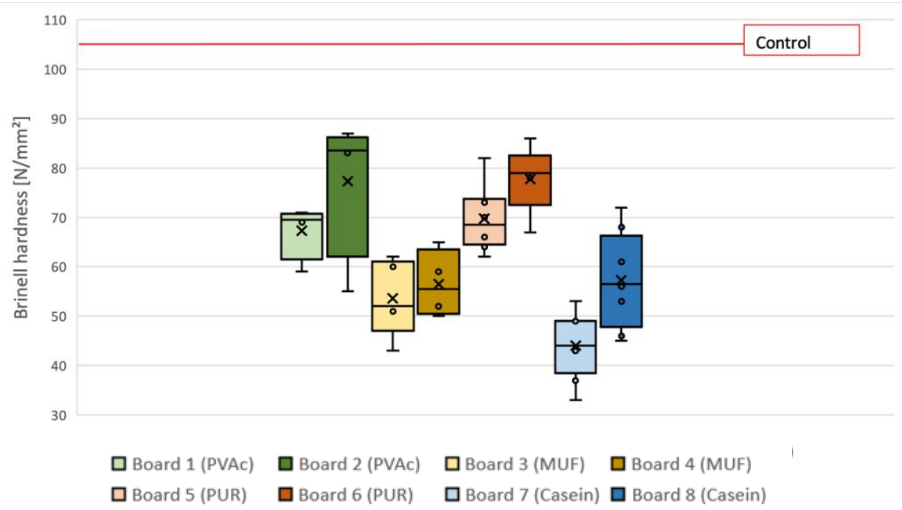

Fig. 11.
Brinell hardness (N/mm^2) of the 7-ply pre-compacted beech veneer LVP.

CONCLUSIONS

To reduce or eliminate a major problem, namely the damage due to stretching and/or buckling of the veneer in the manufacture of laminated veneer products, pre-compression of veneer sheets can represent an alternative especially for the high densified engineered composites. The viscoelastic nature of beech veneers plays an important role in compression and densification. In this study, dimensional stability of LVP was influenced by the veneer compression and was predominantly affected by decreasing material´s hygroscopicity when using other adhesives than PF resins, formation of cross-linkages in the molecules, and the release of stress accumulated during compression. Veneer pre-compaction and the combination of pre-treated raw material with different adhesives for the manufacture of high densified LVP improved some physical and mechanical properties, e.g. tensile shear strength, significantly higher compared to control samples. With respect to bending strength, water absorption and thickness swelling, the LVP with compressed veneers did not perform better compared to control. Regarding the modulus of elasticity, the PUR-bonded LVP measured higher values compared to the benchmark, also the board manufactured at higher pressure and with MUF adhesive application. The spring-back effect was the lowest (7%) and the highest (14%) for the compressed veneers with MUF, respective casein adhesive application. Analyzing the performance of all resins, results that PUR adhesive spread conferred the boards better dimensional stability, higher MOR and MOE, but lower shear strength, despite this value was higher than that of control. Casein based adhesive used to bond LVP with pre-compressed veneers has potential in further applications for sustainable wood fasteners, considering other hot-pressing parameters and processes (i.e. gluing/adhesive application), to improve dimensional stability and elastic properties of composite. Moreover, the formulation of casein-based adhesive should be improved, by increasing resin´s pot life, reducing the amount used and the press time.

The LVP that make the object of this study can be applied in buildings as wear layers between beams or in contact with other materials (concrete, reinforcement). Their use reduces the cross-section of the element, increases safety during use and significantly reduces the consumption of raw materials, significantly extends the service life and ensures a higher resistance to climatic factors compared to solid wood (i.e. GLT, CLT, SWP).

ACKNOWLEDGMENTS

The authors responsively acknowledge the technical support of DI(FH) Maximilian Pristovnik, Ing. Thomas Wimmer, FH Salzburg, Campus Kuchl, Austria, DI Marek Stevko, Kalesnikoff Co., Castlegar, Canada, Pagholz Co., Loitz, Germany and Raimund Beck Co., Mauerkirchen, Austria

Conflicts of Interest: “The authors declare no conflict of interest.”

CRediT author statement: Gerald Stüger and Jakob Karl: Conceptualization, Marius Cătălin Barbu, Eugenia Mariana Tudor: Methodology, Eugenia Mariana Tudor, Gerald Stüger, Jakob Karl: Data curation, Writing- Original draft preparation. Eugenia Mariana Tudor, Marius Cătălin Barbu: Visualization, Investigation. Marius Cătălin Barbu and Eugenia Mariana Tudor: Supervision, Validation. Eugenia Mariana Tudor, Gerald Stüger, Jakob Karl: Writing- Reviewing and Editing

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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