

Enhancing the bending strength, load-carrying capacity and material efficiency of aspen and black alder plywood through thermo-mechanical densification of face veneers

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ABSTRACT

Many research papers highlight the positive impact of wood densification on mechanical properties of solid wood as well as wood veneers. Previous experimental studies comparing densified to non-densified wood materials of the same thickness consistently demonstrated higher strength properties in bending for densified materials. However, these studies often overlooked an important comparison: the strength and load-carrying capacity of non-densified wood material to its densified state, in which the thickness is reduced and thus the material's moment of inertia. The current study, aims to address this gap for plywood made from low-quality, underutilized hardwood species, encompassing both non-densified and densified veneers. Additionally, these plywood panels are compared with high-quality birch plywood. Plywood samples made from common aspen (*Populus tremula* L.) and black alder (*Alnus glutinosa* L.) species, incorporating densified veneers, are compared to conventional silver birch (*Betula pendula* Roth.) plywood. The study also considers material utilization efficiency. Results showed that plywood made from non-densified aspen and black alder veneers exhibited comparable strength to standard birch plywood, positioning them as competitive alternatives to high-quality wood species. While densified black alder veneers increased strength in average from 83.6 MPa to 126.3 MPa, a loss in load-carrying capacity was observed from 1930 N to 1637 N due to reduced thickness and moment of inertia.

1. Introduction

Climate change, environmental concerns, economic challenges, and the depletion of high-quality materials are compelling the contemporary world to prioritize sustainable, environmentally friendly, and recyclable materials. In response to these global issues, the wood industry is increasingly turning to the utilization of low-quality wood material, enhancing their performance through chemical or physical treatments. Among these methods, wood densification has gained popularity. Generally, wood densification involves mechanical and/or chemical processes, which include compressing the wood to close its voids or filling the cell wall structure with chemicals [1]. Thermo-(hygro)-mechanical wood densification refers to the simultaneous application of temperature, humidity, and mechanical factors, primarily used

to improve the mechanical and surface properties of wood [2,3]. By controlling the moisture content of the raw material, the preheating stage, the pressing temperature and time, and the compression ratio, the extent and location of wood cell-wall deformation can be controlled. This allows preparation of densified wood products with high variation in density distribution. Common methods are bulk densification [4], surface densification [5] and sandwiched compressed wood [6,7].

The densification process has been applied to wood veneers that have been previously peeled or sliced. In the veneer densification process, much shorter densification times and lower pressures have been applied compared to solid wood. Short-term thermomechanical densification for the veneers can be successfully conducted in as little as 4 minutes [8]. Moreover, veneers, being relatively thin and predominantly oriented in the radial direction allow for a more even distribution of cell

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deformation across their faces than in thicker solid wood pieces, which can exhibit large variation in growth ring orientation towards the densification direction [9]. It has been demonstrated that densification leads to an increase in the tensile strength of veneers and solid wood [10–12], a reduction in surface roughness [13–16], an increase in contact angle [17], a decrease in wettability [15,18], and a reduction in glue consumption [13–15]. Additionally, numerous studies have indicated that the densification of veneers enhances the bending properties of plywood when compared to plywood of the same thickness composed of non-densified veneers [13–16]. Jakob et al. [19] studied the partial delignification and densification of spruce veneers, followed by plywood production, which resulted in a clear increase in mechanical performance. Plywood made from densified veneers throughout the structure was also studied by Bekhta et al. [20]. To optimize plywood properties, the approach of surface densification of wood can be applied to plywood production. Here the density increases and thus the improvement of mechanical properties is limited to the surface area of the material. Wang et al. [21] used face veneers with high-moisture content and core veneers with low-moisture content and due to moisture-induced differences in the plasticization of the veneer layers, the face veneers were thermo-mechanically densified during this plywood preparation process. However, the authors concluded that this process should be further developed.

Alternatively, the density difference can also be created through multilayered veneer structures. Kallakas et al. [22] examined various lay-up systems and identified that the most favourable alternative to birch plywood, in terms of bending properties, could be a direction core combination of alder and birch veneers. This finding was further supported by Akkurt et al. [23], who demonstrated a 20 % increase in strength in combi black alder plywood with birch face veneers compared to pure black alder plywood in bending along the grain direction. Additionally, Akkurt et al. [23] explored the combination of different veneer thicknesses, revealing a potential reduction in overall glue consumption by using thicker veneer layers. The lowest glue consumption was observed with 2.6 mm aspen plywood and aspen combi plywood, exhibiting 34 %–40 % lower consumption compared to birch plywood and nearly 50 % less than 1.5 mm veneer aspen or combi-aspen plywood. Bekhta et al. [16] found that plywood panels made from a mixture of species exhibited higher bending properties compared to panels made solely from black alder veneers.

As it has been shown, plywood properties can be influenced by the layups system and choice of species. Additionally, the properties of individual veneers can be altered through thermo-mechanical densification, which can then be used for veneers in plywood. Bekhta et al. [18] prepared plywood from different combinations of non-densified and densified veneers with same veneer thicknesses. The lay-up schemes incorporating densified birch face veneers in combination with non-densified alder core veneers were identified as the most optimal when evaluating the shear strength, bending strength, and modulus of elasticity (MOE) values of mixed-species plywood panels. These findings imply, that veneers from low-quality wood species could be densified and used as face veneers to increase the utilization of low-cost hardwood species instead of employing high-quality veneers.

The objective of this work was to investigate whether plywood made through the selective densification of face veneer layers of low-quality wood species, specifically aspen and black alder, can achieve or surpass mechanical strength characteristics comparable to traditionally produced high-quality birch plywood. This work also demonstrates how densification can be utilized to increase bending strength with minimal sacrifice to load-carrying capacity. This was achieved by densifying the low-quality wood species and incorporating them into the face veneer layers of aspen and black alder plywood.

2. Materials and methods

2.1. Wood materials

Veneers of three different wood species were used for plywood production in this study: silver birch (*Betula pendula* Roth) (av. 585 kg/m³), black alder (*Alnus glutinosa* L.) (av. 440 kg/m³), and common aspen (*Populus tremula* L.) (av. 420 kg/m³). Aspen and black alder wood species were selected due to their widespread availability, offering an alternative to birch. These wood species are recognized as low-quality when compared to birch, characterized by their lower density and strength [23]. The choice of birch as the control species is grounded in its status as the most commercially utilized hardwood species in the Baltics and Finland for plywood production. This selection allows for a comprehensive comparison between the alternative, lower-quality options and the industry-standard birch. The logs were freshly felled in September 2022 from Kärü, Rapla County in Estonia by State Forest Management Centre (RMK). Mean stand age was 76 years, and logs had quality class B and C [24]. The log nominal lengths were 3 m, and average diameters were 24 cm for birch, 26 cm for black alder, and 33 cm for aspen. The logs underwent visual sorting, and those with fewer knots, and no signs of decay were selected for the veneer production process.

2.2. Veneer manufacturing process

The logs, initially in length 3000 mm, were trimmed to a peeler log length ranging from 1200 to 1400 mm. Subsequently, they were fully immersed in a log soaking water tank for 24 hours at 40 °C. Prior to peeling, the logs were debarked and various parameters such as log internal temperature, moisture content (MC), length, and annual ring widths were meticulously recorded. The peeling process was executed using a Raute industrial scale peeling lathe (model 3HV66, Raute Oyj, Lahti, Finland) with specific parameters: peeling speed 60 m/min, knife angle of 21°, and a compression rate of 10 %. Birch, black alder, and aspen veneers were rotary peeled with nominal thickness of 1.5 mm for standard plywood, also veneers with nominal thickness of 2.6 mm and 3.0 mm for aspen and 3.0 mm veneers for black alder peeled for densification to 1.5 mm.

After the peeling process, the veneers were precisely cut into dimensions of 900 × 450 mm² (Length × Width) using a guillotine. Subsequently, all specimens underwent drying at 170 °C in a laboratory veneer dryer (Raute Oyj, Lahti, Finland). The drying durations varied based on wood species and veneer thickness from 150 s to 420 s. Following the drying process, the veneers were stored at 25 °C and 20 % RH in the Laboratory of Wood Technology at Tallinn University of Technology, Tallinn, Estonia, to maintain a targeted MC of 5 %, which is necessary for subsequent gluing applications.

After drying and conditioning, veneers without any defects were carefully selected and further cut into sizes of 280 × 430 mm² (L × T). These selected veneers were then sent to Luleå University of Technology for the densification process. Simultaneously, the rest of the veneers were stored to produce non-densified veneers and plywood.

2.3. Densification

Thermo-mechanical densification of the specimens was carried out at Luleå University of Technology in Northern Sweden. Densified veneers, measuring 50 × 200 mm² for the subsequent manufacture of plywood, along with additional specimens for characterizing the densified veneers, were produced. Before densification, the specimens underwent conditioning at 20 ± 2 °C and 65 ± 5 % RH until equilibrium moisture content (EMC) was achieved. This increase from a MC of 5 % to 10 % was deliberately allowed to reduce the glass-transition temperature during densification, enabling densification at relatively low temperatures [25,26].

The non-densified veneers underwent uniaxial compression in a laboratory hot press (Fjellman Press AB, Mariestad, Sweden), with both platens heated to 150 °C. The target thickness was set at 1.5 mm and was maintained by mechanical stops. Starting with initial thicknesses of 3.0 and 2.6 mm, this resulted in target compression ratios of 50 % and 42 %, respectively. The specimens were positioned on the heated platen, and the pressing cycle commenced. During the time between cycle start and full contact with both press hotplates, a veneer specimen lost approximately 1 % in MC. A low contact pressure was initially applied and held for 10 s to elevate the surface temperature, thereby plasticizing the wood. The pressure was then increased, resulting in a compression rate of 0.1 mm/s until the target thickness was reached. The specimens were maintained under pressure and heat for 240 s, after which the press was cooled through internal water circulation until the platen temperature reached 35 °C (6 min). After the cooling process, the pressure was released. Subsequently, all specimens were tightly wrapped in plastic film to prevent moisture changes before further processing.

2.4. Characterization of non-densified and densified veneers

Four sheets per species and thickness were processed into specimens for the characterization of the veneers. MC was determined by using the gravimetric method after oven drying at 103 ± 3 °C until the specimens were fully dried. Density profiles (DPs) were obtained through X-ray densitometry using a laboratory DP analyser (DENSE-LAB X, Electronic Wood System GmbH, Hameln, Germany) with a spatial resolution of the X-ray beam set at 50 μ m. Measurements were conducted with step intervals of 4 μ m in the radial direction, and the specimens measured 50×30 mm². For each sheet, DPs were collected for one non-densified and

four densified specimens.

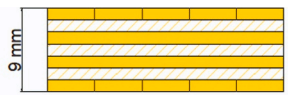
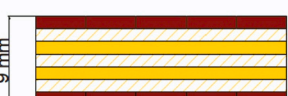
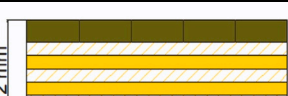
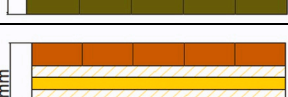
Surface roughness of the tight side of the veneer was determined before and after densification on 4 specimens per veneer sheet using light microscopy with a digital microscope (DSX1000, Olympus Corporation, Tokyo, Japan). The surface roughness was calculated from the height map of the collected image of the bark-side surface for an area of interest measuring 50×30 mm². The roughness was expressed as the 3D roughness parameter root mean square height (Sq), maximum height (Sv), and arithmetical mean height (Sa).

Tension test samples were conditioned at 65 % RH and 20 °C. Subsequently, tension strength parallel to the grain was tested in accordance with DIN EN 789:2004, utilizing an MTS Criterion Series 40 universal testing machine (MTS System Corporation, Eden Prairie, MN, USA) equipped with a 10 kN load cell. The tension rate employed was 0.02 mm/s, and the dog bone-shaped specimens measured 30×100 mm². For each veneer sheet, five non-densified and five densified specimens were tested.

2.5. Lay-up structures for plywood

The plywood lay-up schemas were developed using the standard cross-band construction method, resulting in five plywood types with seven layers, as described in Table 1. For plywood types II and III, face veneers were created by stitching together six small pieces of densified veneer, each 1.5 mm thick, resulting in face veneer sheets measuring $200 \text{ mm} \times 300 \text{ mm}$. The middle layers in these samples were composed of a single piece measuring $200 \text{ mm} \times 300 \text{ mm} \times 1.5 \text{ mm}$ of non-densified veneer. Type I plywood served as the control sample, identical in size to types II to III, with the only difference being that the face veneers were

Table 1
Lay-up of plywood types with layer coding.

Plywood type		Lay-up
I		N ^{1.5} -N ^{1.5} -N ^{1.5} -N ^{1.5} -N ^{1.5} -N ^{1.5} -N ^{1.5}
II		D ^{2.6→1.5} -N ^{1.5} -N ^{1.5} -N ^{1.5} -N ^{1.5} -N ^{1.5} -D ^{2.6→1.5}
III		D ^{3.0→1.5} -N ^{1.5} -N ^{1.5} -N ^{1.5} -N ^{1.5} -N ^{1.5} -D ^{3.0→1.5}
IV		N ^{2.6} -N ^{1.5} -N ^{1.5} -N ^{1.5} -N ^{1.5} -N ^{1.5} -N ^{2.6}
V		N ^{3.0} -N ^{1.5} -N ^{1.5} -N ^{1.5} -N ^{1.5} -N ^{1.5} -N ^{3.0}

 1.5 mm non-densified grain direction
 1.5 mm non-densified crosswise direction

 2.6 mm to 1.5 mm densified grain direction
 2.6 mm non-densified grain direction

 3.0 mm to 1.5 mm densified grain direction
 3.0 mm non-densified grain direction

*N-non densified veneer; D-densified veneer; superscripts show the veneer thicknesses.

made of non-densified veneer. Two types of densified veneers were used for aspen, with thicknesses reduced from 2.6 mm to 1.5 mm and from 3.0 mm to 1.5 mm. In contrast, only 3.0 mm black alder veneers were densified to 1.5 mm. Finally, types IV and V plywood were prepared using the initial thickness of densified veneers before densification, with no densification applied to the face layers, resulting in 12 mm thick plywood as the final plywood thickness. This was done for comparison with 9 mm plywood with densified face veneers.

2.6. Plywood manufacturing process

The adhesive process employed phenol formaldehyde (PF) resin (Prefer Resins Finland Oy, Hamina, Finland). The application of adhesive was carried out using a glue roller (Black Bros 22-D) with a targeted spread rate of 160 g/m². The total amount of applied glue was determined by weighing the veneers both before and after spreading. Subsequently, the panels underwent hot-pressing at 130 °C, applying a pressing pressure of 1.4 MPa. To ensure complete curing of the adhesive, 9 mm thick panes were pressed for 9 minutes, and 12 mm panels were pressed for 10 minutes.

A total of 27 plywood samples were prepared for the study. Aspen veneers, initially with thicknesses of 3.0 mm and 2.6 mm, underwent densification to 1.5 mm to evaluate the impact of the densification ratio. Similarly, black alder veneers, originally 3.0 mm thick, were also densified to 1.5 mm. This step aimed to observe the effects of densification across different wood species and various veneer thicknesses.

2.7. Standards and methods of analysis

Specimen dimensions were measured following European Standard EN325:2012 after conditioning at 20 ± 2 °C and 65 ± 5 % RH in the climatic chamber (ILKA KTK800). Thickness measurements adhered to EN315:2002, while density determinations were conducted as per EN323:2002. All density measurements were taken after conditioning specimens at a relative humidity of 65 ± 5 % and a temperature of 20 ± 2 °C.

Plywood bond quality underwent testing according to standards EN 314-1:2005 and EN 314-2:1999, class 3. This involved soaking the plywood in water at 20 ± 3 °C for 24 hours, followed by immersion in boiling water for 4 hours, then drying in a ventilated oven for 16 hours at 60 ± 3 °C, followed by another 4-hour immersion in boiling water, and finally cooling in water at 20 ± 3 °C for 1 hour. Subsequently, the plywood specimens were tested using a universal testing machine (Zwick/Roell Z050, ZwickRoell GmbH, Germany).

Bending properties were evaluated through a three-point bending test per EN310:2002, utilizing a 50 kN universal testing machine (Zwick/Roell Z050, ZwickRoell GmbH, Germany). All test specimens were conditioned at 20 ± 2 °C and 65 ± 5 % RH for at least 24 hours, as specified in the standard.

The effects of different lay-up schemas and the comparison of non-densified and densified plywood samples on strength properties were analysed using analysis of variance (ANOVA) with a 95 % confidence level of significance, performed using Microsoft Excel. The Bonferroni test was employed to determine significant differences.

3. Results

3.1. Glue consumption and density

The amount of glue absorbed varied depending on the wood species used for veneers, veneer thickness, and whether densification was applied. The lowest glue consumption was observed in 9 mm birch plywood samples, with an average value of 160 g/m². In contrast, the highest glue consumption was found in 12 mm aspen plywood, where all layers consisted of non-densified veneers, averaging 187 g/m². For the same thickness of plywood, birch and black alder plywood with non-

densified veneers showed similar glue consumption, whereas aspen plywood with non-densified veneers exhibited significantly higher consumption, aligning with findings reported in [20,22,23].

The lowest density was observed in aspen type IV plywood samples, measuring 517 kg/m³, while the highest density was recorded in black alder type III plywood samples, reaching 846 kg/m³. ANOVA analysis indicated that plywood density is significantly influenced by the veneer species. Furthermore, ANOVA analysis revealed that the density of aspen plywood with densified face veneers (2.6 mm and 3.0 mm to 1.5 mm) was significantly higher than that of aspen plywood with non-densified veneers (1.5 mm). A similar trend was observed with black alder plywood. This highlights the substantial impact of adding densified veneers to plywood on its final density. The average densities of plywood types were presented in Fig. 1.

3.2. Densification results

The effect of the thermo-mechanical densification of the individual veneers are presented in Table 2 and Table 3. Stoppers with a thickness of 1.5 mm were employed during the densification process to ensure uniform thickness. Consequently, varying pressures were applied to different wood species and veneer thicknesses to achieve the desired thickness. As indicated by the tables, the applied pressure was greater for wood species with higher density, and for veneers of differing thicknesses within the same species, it correlated with the compression ratio. For example, both 2.6 mm and 3.0 mm aspen veneers were densified to a final thickness of 1.5 mm, resulting in compression ratios of 42.3 % and 50 %, respectively. It's important to note that the higher the compression ratio, the greater the applied pressure required to achieve the desired thickness.

Tensile strength experienced a significant increase due to densification, primarily due to the approximately halved cross-sectional area of the test specimens. However, the increase in load-carrying capacity (maximum force) was not notably significant. Surface roughness markedly decreased across all derived parameters, particularly noticeable for aspen, as non-densified aspen veneers tend to exhibit a very fuzzy surface. After densification, there was no significant difference in surface roughness between aspen and black alder specimens.

3.3. Bonding

Standard plywood and plywood with densified face veneers underwent bond strength testing, the results of which are summarized in Table 4. The test results indicate that there was no significant correlation between densification and bond strength in plywood. This conclusion aligns with previous research where no notable change in bond strength was observed [5,15,17]. The observed variance in bonding strength was found to be significant only between different wood species, with birch exhibiting the highest bond strength (av. 2.23 MPa) and aspen displaying the lowest (av. 1.53 MPa).

3.4. Bending strength, maximum force and modulus of elasticity

The average values for bending strength (MOR), maximum force (F_{max}), and modulus of elasticity (MOE) were illustrated in Fig. 2 and Fig. 3 for plywood types I to V. Fig. 2 displays the comparison of bending strength and F_{max} values.

Several trends can be observed from the results of the bending strength (σ) and maximum force (F_{max}) comparison. Firstly, among the control samples (type I) of different species, birch plywood exhibited the highest bending strength (σ = 123 MPa) and maximum force values (F_{max} = 1437 N), while aspen showed the lowest values (σ = 82.7 MPa and F_{max} = 946 N, respectively) on average.

Secondly, the utilization of densified veneers at faces significantly increased the bending strength of type II and type III aspen plywood by 13 % and 26 %, respectively, compared to control plywood of type I

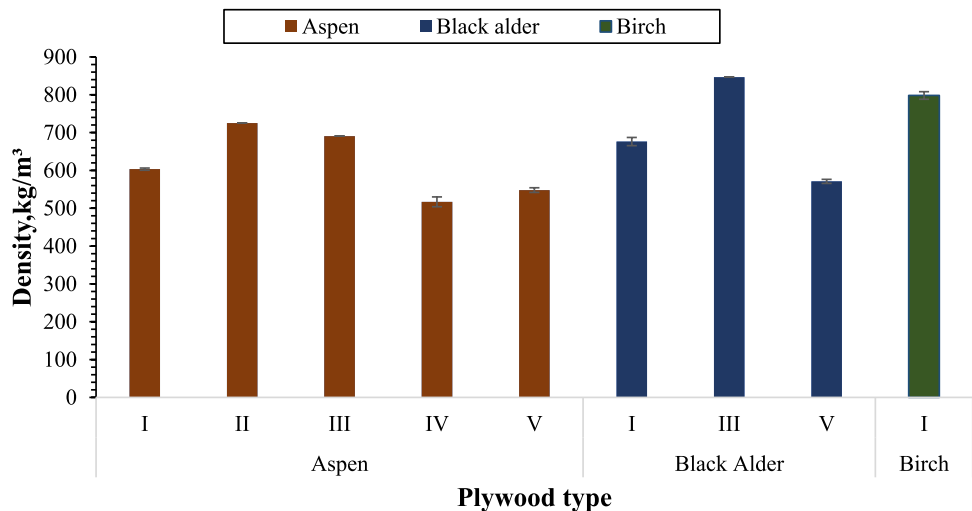


Fig. 1. Densities of plywood from different wood species.

Table 2
Veneer properties before and after densification, and maximum pressure during densification.

Group	Before densification				After densification			
	t (mm)	density (kg/m ³)	MC (%)	Max pressure (MPa)	t (mm)	density (kg/m ³)	effective CR (%)	MC (%)
Aspen 3.0 mm	3.03	398	10.2	5.8	1.49	796	50.9	2.8
Aspen 2.6 mm	2.63	422	9.8	4.1	1.49	695	43.3	3.1
Black Alder 3.0 mm	3.00	488	10.9	7.9	1.49	895	50.2	2.8

* t = thickness, MC = moisture content, effective CR = actual compression ratio.

Table 3
Tensile test properties and surface roughness determined on microscopic images.

Group	Before densification				After densification			
	Tensile strength (MPa)	Sq (μm)	Sv (μm)	Sa (μm)	Tensile strength (MPa)	Sq (μm)	Sv (μm)	Sa (μm)
Aspen 3.0 mm	61	102	342	82	134	9.0	48	5
Aspen 2.6 mm	54	51	153	41	107	7.0	64	5
Black Alder 3.0 mm	57	43	217	35	103	9.6	32	8

*Surface roughness expressed as Sq, Sv and Sa.

Table 4
Bonding test results according to EN314.

Plywood Type	Average of fv, (MPa)	StDev, (MPa)
Aspen		
I	1.72	0.28
II	1.53	0.38
III	1.78	0.02
IV	1.59	0.39
V	1.29	0.23
Black Alder		
I	1.76	0.33
III	1.90	0.03
V	1.84	0.32
Birch		
I	2.29	0.39

aspen plywood with non-densified veneers. This increase was even more pronounced for black alder samples, with a 38 % increase. This finding is supported by other research results [13,16]. The same trend was valid for black alder plywood samples comparing type III and type I plywood. Additionally, the higher the face veneer densification ratio, the greater the increase in strength for type II and type III plywood of aspen,

with a 13 % and 26 % increase, respectively, for face veneers densified to 1.5 mm from 2.6 mm and 3.0 mm, respectively, compared to type I plywood. This trend aligns with observations from the densification process of aspen and fir wood in the literature [27].

Also, when comparing Type V plywood with average bending strengths of 83.6 MPa and 82.9 MPa, to Type III plywood, which have average bending strengths of 126.3 MPa and 104.6 MPa for black alder and aspen, respectively, it was observed that the bending strength significantly increases when densified face veneers are used in plywood production. However, the load-carrying capacity (F_{max}) significantly decreases. The average F_{max} values are 1627 N and 1189 N for Type III, while for Type IV, the average values are 1930 N and 1549 N for black alder and aspen, respectively. This observation is consistent with previous research [12], which implied that the load that can be carried by compressed wood is significantly lower compared to non-densified wood relative to the element's thickness. The same holds true for the comparison of Type IV to Type II aspen plywood for F_{max} .

In the results, the highest bending strength was observed in type III plywood for both aspen and black alder, while the highest F_{max} values were obtained from type V.

The results indicate that densification significantly increases

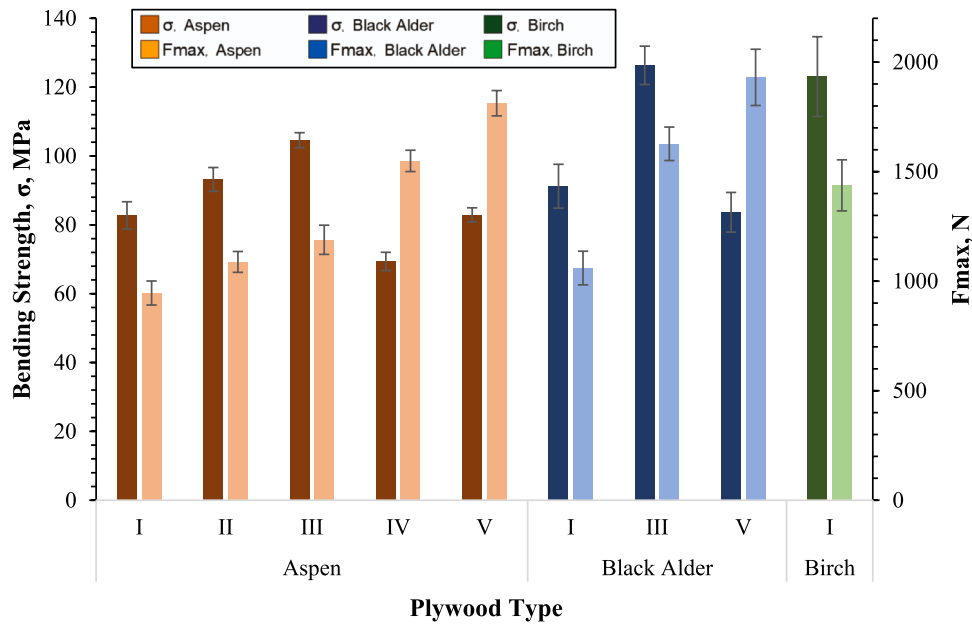


Fig. 2. Bending strength results compared to maximum force carrying capacity (in MPa) for 7-layer plywood.

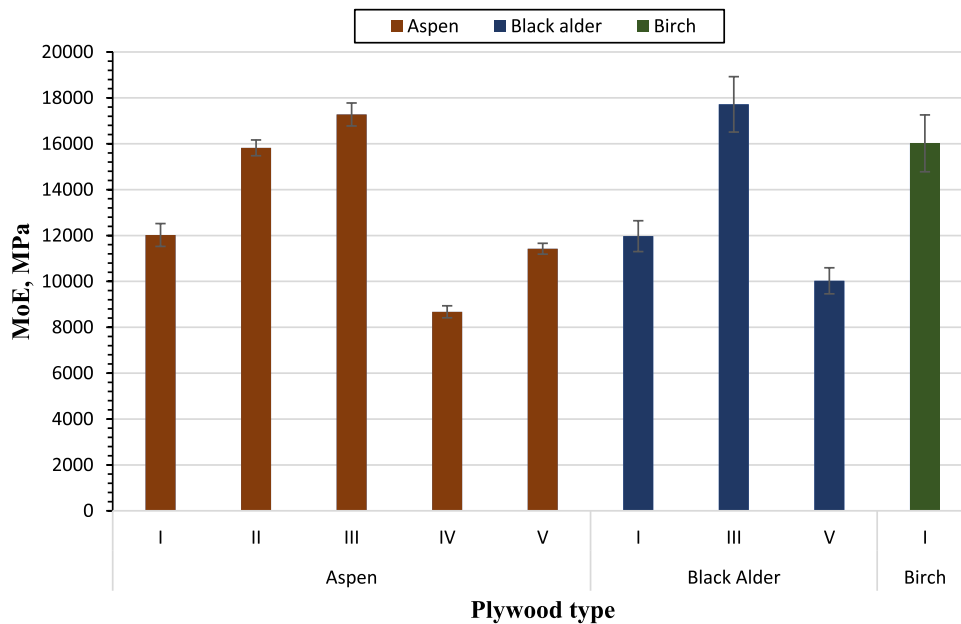


Fig. 3. Modulus of elasticity results (in MPa) for 7-layer plywood.

strength and F_{max} compared to control samples type I, which are at the same thickness as the densified samples. However, while there is an increase in bending strength, there is a significant decrease in the load-carrying capacity of plywood when compared to control samples of type V, which is the plywood with 12 mm thickness when face veneers without densification are used.

Additionally, comparing the type III black alder plywood to standard birch plywood type I, on average, black alder showed higher bending strength than birch, but the difference was not significant. However, for the same plywood, the comparison of F_{max} and MOE showed that black alder had significantly higher results compared to birch plywood of type I.

The Modulus of Elasticity (MOE) results depicted in Fig. 3 also exhibited a similar trend to bending strength. Aspen plywood with 2.6 mm and 3 mm densified face veneers showed an increase in MOE,

measuring 15.8 GPa and 17.3 GPa, respectively, compared to 9 mm non-densified aspen plywood with an MOE of 12.0 GPa. Meanwhile, black alder with 3 mm densified face veneers demonstrated an MOE of 17.7 GPa in comparison to non-densified black alder plywood with an MOE of 12.0 GPa.

Notably, the MOE of black alder III was even significantly higher (11 %) than that of non-densified birch type I plywood, which had an MOE of 16.0 GPa.

3.5. Material usage

In Table 5, these plywood types were compared in terms of material usage. As indicated in Table 5, the highest material usage was observed in plywood with face veneers composed of densified veneers initially measuring 3.0 mm and densified to 1.5 mm, while the lowest was in

Table 5

Material usage in different plywood types.

Wood specie	Plywood type	Material usage
Aspen	Type I	100 %
	Type II	121 %
	Type III	129 %
	Type IV	121 %
	Type V	129 %
Black Alder	Type I	100 %
	Type III	129 %
	Type V	129 %
Birch	Type I	100 %

standard plywood.

4. Discussion

Results indicated that using densified veneers on the faces of plywood significantly increased bending strength, modulus of elasticity (MOE), and load-carrying capacity compared to the same thickness of non-densified plywood. However, it should be noted that the total amount of material used for the same thickness is increasing. If densified veneers were used without densification, the same plywood would be thicker with less bending strength but higher load-carrying capacity. This result aligns with previous research [28], suggesting that the load-carrying capacity decreases in compressed elements compared to non-compressed ones. Also, Avila et al. [29] demonstrated load-displacement curves for both non-densified aspen veneers and densified oil heat-treated aspen samples, which showed that the load-carrying capacity did not change between the densified and treated samples compared to the non-densified ones, while displacement decreased, supporting our findings. However, it appears that Avila et al. overlooked or did not specifically mention that the load-carrying capacity does not change at all for non-densified and densified samples.

This phenomenon is attributed to the nature of the bending strength calculation. The stress formula for tension and compression is calculated using the formula:

$$\text{Stress} = \frac{\text{Force}}{\text{Area}} = \frac{F}{b \times t} \quad (1)$$

where F is in newtons, b is the width in mm, and t is the thickness in mm. However, as seen in the above Eq. (1), if the thickness is reduced to half, assuming the carried force and width are constant, stress will be doubled. When interpreting the results of articles that show less than double the strength, it suggests that densification may have caused damage to the wood material. Arruda et al. [15] compared densified laminated veneer composites with non-densified composites and found a significant increase in compression strength; however, this increase was not proportional to the thickness decrease. Similarly, Bekhta et al. [14] compared 20 % compressed birch veneer plywood samples to non-densified birch veneer samples. In their results, the increase in strength was not proportional to the decrease in thickness. This observation suggests that factors other than thickness, such as changes in the structure or properties of the wood due to compression, may have influenced the strength of the plywood samples.

In bending, strength formulas can vary depending on various testing conditions such as the type of bending test (3-point or 4-point), support conditions (e.g., simply supported, roller supported, cantilever, fixed support), loading style (distributed, point, dynamic), and the position of the load from the supports.

In the case of a 3-point bending test, the stress is calculated according to EN310 using Eq. (2), which is as follows:

$$\text{Bending strength}(\sigma) = \frac{3 \times \text{force} \times \text{length}}{2 \times \text{width} \times \text{thickness}^2} \quad (2)$$

Considering the bending strength Eq. (2) mentioned above, it is

inversely proportional to the square of thickness. Assuming the force-carrying capacity remains unchanged, and the length and width of the samples are constant for both control and densified samples, when the thickness is densified from t to $0.5 t$, then the strength should theoretically increase four times the initial value. However, in the literature, an increase in strength is observed, but not to the extent predicted by the formula. Instead, the increase was typically around 1.1–2.5 times that of non-densified samples [2,10,11,12,14,15,17,18,20,25,29,30,31,32,33].

A few research papers have shown a higher increase in bending strength than expected by the formula, but they did not provide values of $F_{\max}$ to assess if there is a decrease in load-carrying capacity or not. One study demonstrated that subjecting samples to around 20 minutes of pretreatment at 100 °C resulted in a greater increase than expected by the bending formula calculation [17].

Several factors should be considered: since thickness is reduced after densification, the moment arm for the couple forces of tension and compression is decreased. Even if the load carried by the top fibres were doubled, the thickness square effect would diminish this effect, resulting in carrying less load. This phenomenon is observed in many articles where densification decreased the thickness to half and only doubled the strength, indicating a loss in load-carrying capacity [29,30,34].

Some literature [25,32] examines the relationship between bending strength and density values to assess the benefits of densification relative to density. This approach provides an alternative perspective compared to solely evaluating bending strengths, which is more relevant for tension and bending strengths to ascertain the effectiveness of densification. However, a key consideration that is often overlooked is the non-linear relationship between density and bending strength. This is because bending strength is inversely proportional to the square of the thickness, a factor that is not adequately captured in this approach. Additionally, there are findings in the literature showing either a decrease or no change in bending strength [14,20,31,35].

The force exerted in bending can be calculated from equation Eq. (2) as

$$\text{Force} = \frac{2 \times \text{bending strength} \times \text{width} \times \text{thickness}^2}{3 \times \text{length}} \quad (3)$$

If consider the Eq. (3), and assuming that the bending strength is doubled due to densification, the total force carried by the sample would be just half of that of the non-densified sample due to the reduced thickness.

In our tests, we had the opportunity to compare the results of samples with face veneers densified according to the above formulas.

Considering samples with 3 mm non-densified face veneers and densified to 1.5 mm, the total thickness for 7 layers becomes 9 mm after plywood cold and hot-pressing processes. If these were used without densification, the total thickness would be 12 mm. In this situation, the new thickness would be from 12 mm to 9 mm, making the new thickness as 0.75 t (assuming initial $t_0 = 12$ mm). If we are making a replacement in Eq. (3) for bending strength and force, assuming the width of the samples is the same and the length between supports is the same, the results would be:

Bending strength after densification, assuming carried force, width, and length did not change (which is like that in our conditions for length and width and $t = 0.75 t_0$)

$$\sigma_d = \frac{3 \times F \times L}{2 \times b \times (0.75)^2} = 1.78 \sigma_i \quad (4)$$

When examining the black alder samples (type III and V) from Fig. 2, it is observed that the bending strength of the non-densified 12 mm sample is 83.64 MPa. Multiplying it by 1.78 (as shown above) would result in an expected stress of 148.9 MPa. However, the test results showed that the bending strength of the densified sample was 126.3 MPa. Since the width and length were constant, it was expected that the load-carrying capacity of densified samples would be decreased.

Upon further examination of Fig. 2, it is evident that the non-densified sample of 12 mm carries 1930 N, while the densified sample carries 1627 newtons, which is exactly proportional to the loss of strength. Calculating based on the theoretical expectation ($126.3 / 148.9 \times 1927 = 1634$ N), there is a 16 percent loss in load-carrying capacity, which is much less than theoretically calculated using all layers densified veneers, resulting in a 50 percent loss of load-carrying capacity. This indicates that veneer densification has a decreasing effect on load-carrying capacity. However, there is still an open area to decrease the loss of strength by applying more layers and using face veneers densified, which can increase the moment arm and decrease the loss of load-carrying capacity.

However, in the literature, mostly bending strength is observed, but $F_{\max}$ values are not analysed [2,11,12,13,14,15,16,17,18,20,25,27,29,30,32,34,36,37].

This analysis reveals that while densification may enhance bending strength, it leads to a loss in total load-carrying capacity compared to non-densified materials. Nevertheless, there is still an increase in load-carrying capacity for the same thickness of 9 mm. In summary, if there is no dimensional limitation for thickness in usage, it is advisable to use non-densified veneers for plywood production. Conversely, if there is a dimensional limitation, using densified veneers in plywood production can offer the advantage of smaller dimensions with high strength. Therefore, employing densified veneers primarily at the top layers yields higher strength compared to the same thickness, without causing significant load-carrying capacity loss compared to non-densified veneers plywood, while providing dimensional advantages.

It can also be noted that when comparing the same thickness of non-densified samples, face veneers densified samples exhibit higher strength, modulus of elasticity, and load-carrying capacity. Depending on the final usage of the face veneer densified plywood, there are both advantages and disadvantages.

Furthermore, the same discussions apply to modulus of elasticity; even though modulus of elasticity increases significantly, it does not proportionally increase with thickness changes. In EN310 the formula for calculating MOE is given as Eq. (5):

$$E_m = \frac{l_1^3 \times (F_2 - F_1)}{4 \times b \times l^3 (a_2 - a_1)} \quad (5)$$

According to theoretical expectations, when the thickness is reduced in densification to the half, the Modulus of Elasticity (MOE) should increase eightfold, as it is inversely proportional to the cubic of thickness. However, the actual research results indicated that the increase in MOE ranges between 1.5 and 2 times, which suggests that the observed increase is not as substantial as predicted by the theoretical model [15,16,17,18,20,25,27,28,29].

In our tests, by putting $0.75 t_0$ in the formula the expected increase in MOE should be 2.37 times higher of non-densified same thickness sample, however in tests conducted, increase was 1.77 times. This emphasizes once more that densification has a detrimental impact on load-carrying capacity, leading to Modulus of Elasticity (MOE) results that are lower than anticipated.

In addition, veneer densification poses challenges, notably the occurrences of spring back and set recovery effects. In the spring back phenomenon, densified wood elastically reverts to its original shape immediately after the pressing process. Subsequently, with water contact, set recovery takes place, causing the wood to return to its initial thickness. Although attempts have been made to address these effects through chemical modification before densification or post-heat and steam treatments, research indicates that elevated temperatures during these processes may result in a loss of strength in densified wood [11,13,17,20,31,32,34]. Furthermore, certain studies have explored the removal of lignin and hemicellulose from wood. These chemical components of wood were believed to contribute to set recovery, also known as shape memory, during the densification process [18,29]. Moreover,

the set recovery effect contributes to dimensional stability issues. Several research studies have indicated that non-densified samples exhibit superior dimensional stability compared to their densified counterparts [14,15].

5. Conclusions

Based on the study, the following conclusions can be drawn:

- Densification of the face veneers increases bending strength and exhibited higher stiffness values for the same thickness of plywood. Specifically, densification improves bending strength (from 82.7 MPa to 104.6 MPa for aspen and from 91.2 MPa to 126.3 MPa for black alder) and increases stiffness (from 12.0 GPa to 17.3 GPa for aspen and from 12.0 GPa to 17.7 GPa for black alder) in type III plywood panels compared to type I plywood panels.
- Densified veneers had lower surface roughness, but it didn't affect the bonding quality of non-densified and densified veneers.
- However, if there is no dimensional limitation to material thickness and the plywood will be subjected to bending forces, it is better to use veneers without densification for plywood manufacturing. This is because non-densified veneers provide higher load-carrying capacity due to greater thickness and moment of inertia, which is proportional to the cubic of thickness.
- Considering plywood production, the total material usage increases when densified veneers are used, considering the densification process's material usage, spring back, and set recovery issues. The advantage of using densification for plywood production in all layers is questionable.
- Densification works better in tension and compression loading conditions, as strength in these situations is directly proportional to the inverse of thickness.
- Using densified veneers only at the top and bottom layers of plywood may increase resistance to the bending forces similarly to all layers densified plywood, with less material usage. Optimizing the number of layers can decrease the loss of load-carrying capacity. With this slight compromise, it becomes possible to produce plywood with smaller thickness dimensions or plywood exhibiting higher bending strength, load-carrying capacity and higher modulus of elasticity when compared to plywood of the same thickness, all without altering the production process.
- To compensate for the loss of load-carrying capacity, the minimum amount of material should be densified and placed as far as possible from the neutral axis to increase the moment of inertia. Fully densifying all the material cannot achieve this, and, on the other hand, no densification will not increase the bending strength.

Author contributions

Conceptualization, T. A.; methodology, T.A, A.S and A.R.; validation, T.A., H.K. and A.R.; formal analysis, T.A. and A.R.; investigation, T. A.; resources, J.K., A.S; A.R data curation, T.A, A.S; writing—original draft preparation, T.A.; writing—review and editing, J.K, H.K. and A.R.; visualization, T.A., A.S; supervision, J.K, A.R.; project administration, J. K.; funding acquisition, J.K., A.S, H.K. and A.R All authors have read and agreed to the published version of the manuscript.

Declaration of Competing Interest

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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Data Availability

Data will be made available on request.

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