DOCTORAL THESIS

# Valorizing low-quality wood species into innovative multilayer engineered wood products

Tolgay Akkurt

TALLINNA TEHNIKAÜLIKOOL
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# Valorizing low-quality wood species into innovative multilayer engineered wood products

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**Declaration:**
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for doctoral or equivalent academic degree.

Tolgay Akkurt

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# Madalakvaliteediliste puiduliikide puidu väärindamine innovatiivseteks kihilisteks inseneripuittoodeteks

TOLGAY AKKURT

KIRJASTUS

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## List of Publications

The list of author's publications, on the basis of which the thesis has been prepared:

I **Akkurt, T**.; Kallakas, H.; Rohumaa, A.; Hunt, C. G.; Kers, J. (2022). Impact of Aspen and Black Alder Substitution in Birch Plywood. Forests, 13 (2), 142.

II Kallakas, H.; **Akkurt, T**.; Scharf, A.; Mühls, F.; Rohumaa, A.; Kers, J. (2024). The Effect of Hardwood Veneer Densification on Plywood Density, Surface Hardness, and Screw Withdrawal Capacity. Forests, 15 (7), #1275.

III **Akkurt, T.**; Rohumaa, A.; Kallakas, H.; Scharf, A.; Kers, J. (2024). Enhancing the bending strength, load-carrying capacity and material efficiency of aspen and black alder plywood through thermo-mechanical densification of face veneers. Construction and Building Materials, 450, #138555.

IV **Akkurt, T.**; Rohumaa, A.; Kers, J. (2025). Effective Wood Veneer Densification by Optimizing Key Parameters: Temperature, Equilibrium Moisture Content, and Pressure. Forests, 16 (6), 969

## Author’s Contribution to the Publications

Contribution to the papers in this thesis are:

I The author decided to methodology, prepared the veneers, manufactured plywoods, prepared test samples, prepared testing plan and calculated glue consumptions and density, conducted mechanical tests, analysed results, prepared article draft and made review changes.

II The author decided to methodology and conceptualized, prepared the veneers, manufactured plywoods, prepared test samples, prepared testing plan, conducted mechanical tests (bending), analysed results, wrote and edited article draft.

III The author decided to methodology and conceptualized, prepared the veneers, manufactured plywoods, prepared test samples, prepared testing plan, conducted mechanical tests (screw withdrawal and hardness), analysed results and edited article draft, prepared visualizations.

IV The author decided to methodology and conceptualized, prepared the veneers, performed veneer densification experiments, prepared test samples, prepared testing plan, evaluated the spring back and set recovery of the densified veneers, analysed results, wrote and edited article draft, prepared visualizations.

## Introduction

Climate change, environmental concerns, economic challenges, and depletion of high-quality forest resources have increased global demand for sustainable, recyclable, and resource-efficient wood materials for use in construction, furniture, flooring and related sectors. Scarcity of softwood species for construction has changed the wood industry focus on improving the performance of low-quality and underutilized wood species through chemical and physical modification techniques (Dong et al., 2022; Pelit & Emiroglu, 2021; Rowell, 2006; Sandberg & Navi, 2013). Among these, thermo-mechanical densification has emerged as a promising approach, significantly enhancing the physical and mechanical properties of wood while supporting resource optimization (Gaff & Gašparík, 2015; Kamke, 2006; Sandberg & Navi, 2013).

Natural wood—especially fast-growing and low-density species—often suffers from limitations such as strength, dimensional stability, and poor surface quality (Kallakas et al., 2020; Rohumaa et al., 2021). These characteristics restrict their use in structural and decorative applications. Densification process, which involve compressing the cellular structure of wood under heat, moisture, and pressure, improves density, strength, surface hardness and dimensional stability(Bekhta & Niemz, 2003; Navi & Girardet, 2000). These improvements make low-density species viable alternatives to high density woods.

In Estonia, black alder and aspen are among the most common low-quality hardwood species. They are abundant but currently underutilized in value-added applications. This highlights a strong potential for sustainable development through densification techniques.

In particular, veneer densification has gained interest for multi-layered engineered wood products. Rotary-peeled veneers are thin and aligned radially, which facilitates uniform compression and cell-wall deformation under densification (Cabral et al., 2022). Compared to solid wood, veneers require low pressures and shorter pressing times, enhancing industrial efficiency (Rautkari et al., 2011; E.-A. Salca & Bekhta, 2021). Research has shown that densified wood led to increased tensile and bending strength, improved surface quality, reduced wettability, and lower adhesive consumption (Bekhta et al., 2017; Pelit & Emiroglu, 2021; E.-A. Salca & Bekhta, 2021; Shi et al., 2020). These enhancements directly translate into improved mechanical performance of multi-layered wood products (Avila et al., 2012; Cencin et al., 2021; Namari et al., 2021).

Densified veneers can be integrated into multi-layered wood products through various means, including bulk densification, surface densification, and sandwiched veneer structures. For instance, selective densification of layers—such as densifying only face veneers (FVD: face veneer densification)—may optimize bending strength and surface quality, while avoiding the potential drawbacks of densifying the entire panel (AVD:all veneer densification), such as compromised load carrying capacity(Morsing, 2000) and increased material brittleness(Bekhta, Salca, et al., 2020; Goring, 1965; Kutnar & Šernek, n.d.; Morsing, 2000).

Recent studies have explored alternative lay-up systems using combinations of species, veneer thicknesses, and densification treatments to optimize performance and reduce costs (Bekhta, Salca, et al., 2020; Cordier et al., 2025; Kallakas et al., 2020).

The effectiveness of densification is closely tied to the parameters such as temperature, pressing pressure and initial equilibrium moisture content (EMC)(C.-H. Fang et al., 2012; Goring, 1965; Kariz et al., 2016). The heat softening of lignin and hemicellulose, particularly above lignin glass transition temperature, allows permanent deformation of cell walls, enabling substantial gains in compressibility and dimensional stability (Goring, 1965). Studies by (Bekhta & Niemz, 2003) and (C. H. Fang et al., 2011) have shown that densification at temperatures between 180-220 °C improves dimensional stability, although excessive heat can reduce bending strength and modulus of elasticity (MOE). Additionally, higher pressures promote greater cell wall collapse and compaction, enhancing final density and strength (Bekhta et al., 2017; Huang et al., 2024; Navi & Girardet, 2000; Yu et al., 2020), while high EMC or steam treatment has been shown to reduce set recovery and aid fixation of densified shape(Kutnar et al., 2009; Rautkari et al., 2011) .

However most existing studies have focused on solid woods or very high processing temperatures, leading to inconstancies in density, dimensional stability and energy efficiency. Moreover, testing methods often lack standardization for densification parameters.

In thesis, it was demonstrated that face veneer densification significantly improved the bending strength, load carrying capacity, screw withdrawal resistance, surface hardness, and material efficiency of aspen and black alder plywood (Paper I, II and III). Building on this, the current study seeks to further refine densification parameters and evaluate their combined effects at lower temperatures, moderate pressures, and varying moisture content levels to optimize densification parameters (Paper IV).

This research grounded in the hypothesis that densification of low-quality hardwood veneers can enhance their physical and mechanical performance to levels comparable with or superior to traditionally used high density species in multi layered engineered wood products. These findings can also be applied to high quality species to further enhance their physical and mechanical properties more in multi layered wood products. Furthermore, it demonstrates that the application of densified veneers as face layers only (FVD) can optimize mechanical performance while minimizing resource and energy use, in contrast to all-layer densification (AVD), which may negatively affect structural load bearing capacity despite increasing overall density and bending strength (Paper II and III).

The novelty of this work lies in several key findings that challenge conventional assumptions in engineered wood product design:

1) Low density hardwoods as viable alternatives: the study demonstrates that lower-quality wood species such as aspen and black alder, when densified appropriately, can serve as sustainable and efficient substitutes for high-quality birch in multi layered engineered wood products (Paper I).
2) Strategic veneer densification: it is shown for the first time that effective densification should be limited to face veneers. Using densified veneers throughout all layers may result in increased density, and it reduces the overall load carrying capacity when compared to undensified, thicker versions (UN-T) made with the same volume of material. This highlights the importance of veneers placement and composition in lay-up design (Paper III).
3) Energy-efficient processing: the research also finds that densification at lower temperatures (e.g., 90 °C) combined with high moisture content and pressure, can achieve comparable or even superior improvements in density to those obtained at higher temperatures (e.g., 210 °C). This insight offers a more energy-efficient and environmentally sustainable alternative for industrial densification practices (Paper IV).

Together, these findings contribute new knowledge to the field of engineered wood products by presenting a comprehensive evaluation of how species selection, veneer treatment, and panel design interplay to influence the performance and sustainability of multi-layered engineered wood products.

## Abbreviations and Symbols

| | |
|---|---|
| AVD | All veneers densified |
| CLT | Cross laminated timber |
| CR | Compression Ratio |
| DR | Densification Ratio |
| EMC | Equilibrium moisture content |
| FVD | Face veneers densified |
| LVL | Laminated veneer lumber |
| MOE | Flexural modulus |
| MOR | Flexural strength |
| MC | Moisture content |
| RMK | State forest management centre |
| SWC | Screw withdrawal capacity |
| TMD | Thermo-mechanical densification |
| UN | Undensified |
| UN-T | Undensified thick |

# 1 Literature review

## 1.1 Overview of multi-layered engineered wood composites

Multi-layered Engineered wood composites are wood based materials composed of multiple layers of wood or wood-based materials bonded together, typically with adhesives. These layers may be oriented in the same grain direction—as in laminated veneer lumber (LVL)—or with alternating grain directions— as in plywood or cross laminated timber (CLT)—to enhance strength, structural stability, durability, and resistance to environmental changes. Cross lamination is particularly effective in minimizing expansion and contraction due to moisture and temperature fluctuations. These products are widely used in applications such as flooring, structural beams, columns, and panels as well as in furniture and interior design. Among these, structural variants form the core building materials for modern timber construction.

## 1.2 Wood species for engineered wood composites

Various wood species are used in industrial multi-layered engineered wood composites, selected based on availability, mechanical, surface properties, and intended application. Globally species such as cedar, redwood, pine, spruce, Douglas fir, larch, birch, beech, oak, maple, walnut, poplar, black alder, mountain ash, basswood etc are applied in different combinations. Among these birch, pine, spruce, Douglas fir and poplar are the most commonly used in large-scale multi layered wood product manufacturing(Bekhta et al., 2021; Bekhta, Müller, et al., 2020; Chang et al., 2017; Follrich et al., 2006). For instance, spruce is widely used for CLT while birch, spruce and beech are common in LVL.

In the Baltic and Nordic regions, multi-layered engineered wood production is predominantly based on birch, spruce, and poplar veneers due to their availability and favorable mechanical properties (Cordier et al., 2025; Setter et al., 2021). Birch in particular, is widely used for high density, high strength and surface quality (Bekhta et al., 2023; Rohumaa et al., 2021).

However increasing concerns over sustainable resource utilization and depletion of high-quality birch forests highlight the need to diversify the raw material base in multi-layered wood products. This has drawn atention to underutilized native hardwoods, such as aspen (Populus tremula) and black alder (alnus glutonisa), as promising alternatives.

In Estonia, birch is the most dominant hardwood species, covering approximately 26.6% of the total forest area. Aspen and black alder account for about 4.3% and 2.4%, respectively of the total forest area (RMK annual report, 2020), which underlines their strategic importance in the local wood supply chain.

Despite their abundance, aspen and black alder remain underutilized in value-added wood products such as plywood and LVL. Tradionatially considered low-grade species due to their lower density and mechanical performance compared to birch, their application has been limited. However recent advances in thermo-mechanical densificaton and hybrid lay-up strategies have significantly enhanced the potential of these species to replace or supplement birch in these wood products. Also these species have gained attention for cost effective and light-weight applications.

Estonia's wood sector plays a critical role in national economy. As of 2018, approximately 35000 people were employed in the wood industry, reflecting the sectors susbstantial contribution to employement and regional development (Metsa-ja

puidutööstus, 2018). Given in this thesis , utlizing aspen and black alder more effectively, in engineered wood products would not only promote sustainable forestry practices but also support local industry growth by expanding the raw material base.
These factors underline the importance of research in alternative hardwood species for multi-layered engineered composites. Enhancing the performance of aspen and black alder through densification and hybrid design strategies offers a promising path toward greater resource efficiency, environmental sustainability, and economic resilience in Estonia's wood processing industry.

## 1.3 Veneer and plywood manufacturing process

The manufacturing of veneer begins with log selection; typically, straight and defect free logs are chosen to ensure high-quality output. The selected logs are then soaked in hot water or steamed to soften the lignin and hemicellulose, facilitating smoother cutting and minimizing surface defects(Goring, 1965; Salmen, 1982) .

After soaking, the logs are debarked, and then peeled using rotary lathes or sliced into thin veneer sheets. Slicing is generally used for decorative face veneers, although it is less efficient in material use (Ang Schramm, 2003; Craig L. Forbes, 1997). Then, the peeled or sliced veneers are cut to the desired dimensions, followed by controlled drying to reach a target equilibrium moisture content (EMC) of 5-8%. This drying stage is crucial to avoid defects such as warping, splitting or uneven shrinkage, ensuring dimensional stability and proper adhesive bonding in later stages (Christiansen, 1991; Šernek & Helm, 2002)
The plywood is manufactured by binding multi layers of veneers in crosswise direction by applying adhesives and alternating veneers in grain direction. Alternation in direction significantly enhances structural integrity, stiffness and resistance to splitting. Adhesives such as phenol-formaldehyde (PF) for exterior-grade plywood or urea-formaldehyde (UF) for interior applications are applied to bond the layers.

Pressing operations are conducted in two stages: cold pressing and hot pressing. Cold pressing helps pre-bond the veneers and allows adhesive penetration and pre-curing, while hot pressing finalizes the bonding under high pressure (typically 1–1.8 MPa) and temperature (130–150 °C) to ensure full curing of the resin. After pressing, the panels are cooled, trimmed to size, surface-sanded, and subjected to stringent quality control assessments, including tests for mechanical performance, delamination resistance, and dimensional accuracy.

Wood species selection plays a crucial role in both veneer and plywood manufacturing(Aytekin, 2008). Properties such as wood density, bending strength, surface smoothness, screw withdrawal resistance, and Brinell hardness significantly affect the final performance of multi-layered engineered products(Cabral et al., 2022; Mania et al., 2020; Sandberg & Navi, 2013). Denser woods typically provide higher bending strength and improved surface hardness, leading to better wear resistance and mechanical integrity in structural applications. Moreover, smoother and harder surfaces contribute to lower adhesive consumption and better bonding quality.

Screw withdrawal resistance, which is essential for the durability and reusability of furniture and load-bearing panels, is also closely correlated with density and microstructure of the veneer layers. Brinell hardness determines the surface wear resistance, a critical property for flooring and surfaces exposed to abrasion.

In Estonia, medium-density species such as aspen and black alder (average densities approx. 420–450 kg/m³ and 470–500 kg/m³ at 12% MC, respectively) are being investigated as viable alternatives to high-density birch (approx. 650–670 kg/m³ at 12%

MC), especially in the context of sustainable resource utilization and cost. Studies have shown that when appropriately modified (e.g., via densification), these species can achieve comparable performance levels in plywood applications, including structural and decorative uses.

## 1.4 Wood and veneer densification techniques and applications

Densification enhances wood properties by applying heat and pressure to reduce porosity and increase density. Two major methods are mechanical and thermo-mechanical densification. Thermo-mechanical densification (TMD) involves heating the wood to soften lignin and hemicellulose, followed by compression under controlled conditions. This process enhances mechanical strength, dimensional stability, surface hardness, and resistance to moisture. Densified veneers are used in decorative panels, flooring, and structural composites.

## 1.5 Influence of densification on veneer and engineered wood products

Numerous studies (Bekhta et al., 2017; Pelit & Emiroglu, 2021; E.-A. Salca & Bekhta, 2021) have shown that densification improves surface hardness, modulus of rupture (MOR), and modulus of elasticity (MOE). Densified veneers also demonstrate reduced water absorption and thickness swelling. Set recovery, or the tendency of compressed wood to return to its original dimensions, is a key concern. Parameters such as temperature, pressure, time, and initial moisture content influence the magnitude of set recovery. Several researches reported significant effects of densification temperature on set recovery.

Comparative analysis of densification parameters was performed in current study and others (e.g., Bekhta et al., 2009) have investigated a range of temperatures (90–210°C), pressures (3–12 MPa), and EMC levels (5–14%) to determine optimal conditions for veneer densification. For birch veneers with 5% EMC, density increased significantly from ~550 kg/m³ to 940 kg/m³ at 210°C and 5.4 MPa.

Densified veneers can be used in multi-layered structures such as hybrid plywood, where only outer layers are densified to enhance surface durability while reducing overall material costs. Studies have shown that such configurations improve surface hardness and impact resistance without significantly increasing production costs. The integration of densified layers can also improve bonding efficiency and mechanical uniformity.

In LVL and other engineered products, densified veneers contribute to increased stiffness and load-bearing capacity. The consistent density profile achieved through TMD ensures better performance under long-term loading and cyclic stress. Researchers have explored combining densified and non-densified veneers in strategic layer placements to tailor mechanical performance and weight.

Compression ratio (CR) refers to the percentage reduction in veneer thickness post-densification. Densification ratio (DR) is the increase in density relative to the original density. High CR and DR values generally correlate with improved mechanical properties but may also lead to higher set recovery and internal stress.

## 1.6 Energy efficiency, sustainability, and environmental concerns in densification

Thermo-mechanical densification is energy-intensive, particularly at high temperatures and pressures. Sustainable practices include optimizing pressing schedules, recycling process heat, and utilizing low-grade hardwoods like aspen and black alder. Substituting birch with these species reduces reliance on premium timber and supports circular economy principles. Adhesive selection and emissions from pressing are environmental concerns, requiring careful management to align with sustainability goals.

## 1.7 Gaps in literature and research needs

Despite the growing interest in the use of low-value hardwood species such as aspen and black alder for plywood production, several notable gaps persist in the current body of research. These species are typically characterized by lower density, which is generally associated with reduced mechanical performance. However, their lower log prices and, particularly in the case of aspen, their lighter weight present opportunities for producing cost-effective engineered wood products. Previous research has not thoroughly addressed the influence of veneer thickness and adhesive consumption on the mechanical behaviour of plywood panels made from these species, especially in the context of optimizing material efficiency and mechanical performance.

One critical gap is the limited understanding of how densified and non-densified veneers compare in terms of load-carrying capacity, particularly in bending applications. While densification is often assumed to improve mechanical properties, it may actually reduce load-bearing performance when increased veneer thickness contributes significantly to moment of inertia. In conditions where material thickness is not a limiting factor, non-densified veneers can provide superior bending resistance in load carrying due to their greater cross-sectional dimensions. However, most studies have not evaluated this trade-off comprehensively by comparing densified and non-densified conditions under equivalent structural performance criteria. This creates uncertainty around the real-world benefits of full-layer densification in plywood intended for structural applications.

Moreover, using densified veneers in all plywood layers raises concerns about increased material usage, spring back, and set recovery, all of which contribute to production inefficiencies. While densification tends to perform well under tension and compression, its value in bending applications remains less clear. A promising but underexplored alternative is the selective densification of only the outer (face) layers, which may provide similar or even superior improvements in bending strength and modulus of elasticity with reduced material input and energy consumption. Despite its potential, this selective approach remains insufficiently studied in terms of its balance between mechanical performance and resource efficiency.

Additionally, most existing research on veneer densification has concentrated heavily on the process parameters—such as temperature, pressure, and duration—without fully considering the final product performance in real-world applications like construction. Even though the standard densification methods have been explored for decades, they may no longer be optimal for modern plywood applications where performance-to-cost ratios are increasingly critical. There is a need for a shift in focus from the process itself to the outcomes it produces, including mechanical strength, dimensional stability, and energy efficiency across various lay-up strategies and species combinations.

Finally, previous work has largely focused on softwood species or high-temperature densification processes that may not translate effectively to low-density hardwoods like aspen and black alder. A systematic investigation into optimized densification conditions—involving lower pressures, moderate temperatures, and shorter cycle times—is still lacking. Such optimization would be instrumental for enabling scalable, industrial production of high-performance plywood made from underutilized hardwood resources, while minimizing energy input and improving material utilization.

## 1.8 Objectives

In response to these identified research gaps, the specific objectives of this study are as follows:

- To analyse the effects of temperature, pressing pressure, and initial moisture content on the densification behaviour of low-density hardwood veneers (aspen and black alder), particularly in terms of density, compression ratio, and set recovery.
- To compare the performance of fully densified (AVD) and face-only densified (FVD) plywood panels, focusing on bending strength, load-carrying capacity, surface hardness, screw withdrawal resistance, and material efficiency.
- To determine optimal densification parameters that balance energy efficiency, performance enhancement, and sustainability—particularly through the evaluation of low-temperature, short-cycle densification strategies.
- To evaluate how veneer configuration (species, thickness, placement) influences the mechanical and surface properties of plywood, with a view toward optimizing lay-up design for cost-effective and sustainable production.
- To contribute to the development of energy-efficient industrial densification practices, promoting wider use of underutilized hardwood species in engineered wood products.

# 2 Materials and methods

This chapter provides an overview of materials hardwood species used to prepare veneer and plywood, experimental plan and methods used to assess mechanical and physical properties of the veneer-based materials investigated in this study. The research first focuses on evaluating low quality hardwood plywood made from aspen and black alder species by comparing their density, glue consumption and bending properties with those of control samples made from birch (Paper I). To enhance the performance of these low-quality hardwood species-based plywoods, veneer densification was applied, aiming improvements in mechanical and physical properties such as screw withdrawal resistance and Brinell hardness (Paper II), as well as bending strength (Paper III). Finally, after demonstrating that selective application of densified veneers can elevate the performance of low-quality hardwood plywoods to match the strength levels of birch plywood, further studies were focused on optimization of the densification process parameters. For veneer densification optimization, key parameters such as hot-pressing temperature, equilibrium moisture content, and pressing pressure were selected (Paper IV).

## 2.1 Wood materials

In veneer-based products development, it is crucial to know the origin and background of the logs, as the growth location and conditions are the factors significantly influencing the overall quality of manufactured wood veneers. Important characteristics such as forest density and mix of wood species growing in the stand, place of growth and climate conditions etc all affect growth conditions of single tree and thus the peeled veneer quality. Therefore, in this study, all wood materials were sourced incorporation with Estonian State Forest Management Centre.

Three different wood species were selected for veneer production: silver birch (Betula pendula Roth) (av. 585 kg/m³), common black alder (*Alnus glutinosa* L.) (av. 440 kg/m³) and common aspen (Populus tremula L.) (av. 420 kg/m³). for the study presented in Paper I. The logs for were freshly felled in September 2020 in Käru, Rapla County, Estonia and supplied by State Forest Management Centre (RMK). The average age of stand was 76 years. For the research presented in Paper II, the logs were freshly harvested in October 2022 at Järvselja, Tartu County, Estonia by the Järvselja Learning and Experimental Forest Foundation. The average stand ages, weighted by area, were 59 years for birch, 26 years for black alder, and 66 years for aspen. For papers III and IV, the logs were again sourced from Käru, Rapla County, Estonia and felled in September 2022 by RMK. Mean stand age was 76 years. The log nominal lengths were 3 m and average diameters were 24 cm (birch), 26 cm (black alder), and 33 cm (aspen). For veneer peeling, the logs were visually sorted based on wood defects: small number and dimensions of knots, end checks, no crooking allowed, and no signs of decay was allowed.

## 2.2 Veneer manufacturing

For manufacturing of the veneers, the rotary peeling method described in previous study (Paper I) was used. Logs with three meters in length were cut by chainsaw into peeler blocks ranging from 1200 mm to 1400 mm in length and then immersed in a hot soaking water tank at 40 ◦C for 24 hours. Before peeling, peeler blocks were debarked by hand knives, and variables such as temperature, moisture content (MC), log length, and annual ring widths were measured. Subsequently, the peeler blocks were rotary-peeled into green veneers using an industrial-sized peeling lathe (Model 3HV66; Raute Oyj, Lahti, Finland) with the following settings: peeling speed of 60 rpm, knife sharpening angle of 19◦, and a compression rate of 7%. The nominal veneer thickness was 1.5 mm for aspen, black alder and birch. For densification and control purposes, thicker veneers 3.0 mm for birch, black alder and aspen were peeled. Following the peeling process, the veneer matt was cut into sheets measuring 900 × 450 $mm^2$ using a pneumatic guillotine (Wärtsilä Corporation, Helsinki, Finland). Then, veneer sheets were dried at 170 °C in a laboratory-scale veneer dryer (Raute Oyj, Lahti, Finland). The drying durations varied based on wood species and veneer thickness, as specified in Table 1. After drying, the veneers were stored in a conditioned room at 25 ± 2 °C and 20 ± 5% relative humidity (RH) to achieve a target moisture content of 4.5 ± 1.5%, which is necessary for subsequent gluing in plywood manufacturing.

*Table 1. Drying times of different hardwood veneer thicknesses.*

| | **Veneer Thickness (mm)** | |
|---|---|---|
| **Wood Species** | **1..5** | **3.0** |
| Birch | 150 s | 370 s |
| Black alder | 160 s | 390 s |
| Aspen | 170 s | 420 s |

## 2.3 Veneer densification and parameters of densification

To evaluate the effect of densification on the physical and mechanical properties of wood, a series of thermo-mechanical densification steps were applied. Following peeling, drying and conditioning, defect free veneers were carefully selected and cut into specimens measuring 50 × 200 $mm^2$. These specimens were then conditioned at 20 ± 2 °C and 65 ± 5% RH until they reached an EMC of approximately 12%. This conditioning step was intentionally performed to increase the EMC, thereby lowering the glass transition temperature of the wood (Goring, 1965; Salmen, 1982).

The densification process was carried out at Luleå University of Technology, located in Northern Sweden. A laboratory hot press (HLOP15, Höfer Presstechnik GmbH, Taiskirchen, Germany) was used to uniaxially compress the veneers in radial direction between heated plates set at 150 °C. The target veneer thickness after densification was 1.5 mm, achieved using mechanical stops. A 50% compression ratio was applied, starting from initial thickness of 3.0 mm.

Once the specimens were placed on the heated plates, the pressing cycle was started. During the initial phase each specimen lost approximately 1% of its moisture content before full contact was established with both hot-pressing plates. To facilitate plasticization of lignin, a low contact pressure was applied and maintained for 10 s to raise the surface temperature. Subsequently, the pressing pressure was increased to achieve a compression rate of 0.1 mm/s until the target thickness was achieved. The specimens were then held under pressure at 150 °C for 240 s.

After heating phase, the platens were cooled to 35 °C using the press's internal water circulation system in 6 minutes. The pressure was released once the cooling phase was completed. To prevent moisture fluctuations, each specimen was immediately sealed in plastic film to avoid moisture changes (Paper II and III).

It is important to mention that the above densification process was conducted using a standard approach widely accepted in the field. However, despite decades of research at various levels, this method found to be suboptimal. Most development efforts so far have primarily focused on refining the densification process itself, rather than thoroughly evaluating the final product and its performance characteristics.

As the final stage of the study, to determine the optimum veneer densification parameters (Paper IV), four pressing temperatures were selected: 90 °C, 130 °C, 170 °C, and 210 °C. The lowest temperature, 90 °C, was chosen to investigate the influence of EMC while minimizing energy consumption. The 130 °C temperature setting served as an industrial reference, as it is commonly used in plywood production. A higher temperature of 170 °C was included to maintain a consistent 40 °C interval, enabling clear trend analysis across the temperature range. Lastly, densification temperature setting 210 °C was selected based on literature findings (Bekhta & Niemz, 2003; C.-H. Fang et al., 2012) suggesting that temperatures exceeding 200 °C can reduce set recovery after densification due to chemical softening of lignin.

Three EMC levels were investigated: 5%, 12%, and 20%. The 5% EMC level was achieved by conditioning samples at 20% RH and 25 °C, reflecting standard industry practice for birch veneers. The 12% EMC level, represent typical in-service moisture condition, was obtained at conditions 65% RH and 20 °C. in conditioning chamber The higher 20% EMC level was created in conditioning chamber storage conditions 90% RH and 30 °C. These conditions were chosen because increased MC lowers the glass transition temperature of lignin, thus enhancing plasticization during densification(C.-H. Fang et al., 2012; Kamke & Kutnar, 2010). Although these EMC targets were set during conditioning, the actual EMC of each sample was verified after densification using oven-dry weight measurements.

To investigate the role of pressing pressure in combination with wood EMC and pressing temperature, three pressing pressure levels were applied: 1.8 MPa, 3.6 MPa, and 5.4 MPa. The 1.8 MPa level corresponds to typical industrial conditions for birch plywood pressing. A mid-range pressure of 3.6 MPa was selected to approach the yield point of birch in radial compression. The highest pressure, 5.4 MPa, was chosen to initiate plastic deformation within the wood structure. According to simulations by Aimene et al. (2015), transverse compression of wood perpendicular to the grain enters the plastic region near 6 MPa at 20 °C, supporting the selection of this upper pressure limit. The pressing duration was fixed at 8 min for all conditions.

In total, 36 unique parameter combinations were formed by varying temperature (4 levels), EMC (3 levels), and pressure (3 levels). For each combination, 6 samples were densified, resulting in 216 densified veneer samples prepared.

## 2.4 Lay-up schemas and plywood manufacturing

Firstly, to compare physical and mechanical properties of different low-quality wood species like black alder and aspen, with birch control sample the lay-up schemas for veneer-based wood composites were developed using the standard cross-band plywood construction method (Paper I). This resulted in the production of five plywood types, each with dimensions of 450 x 900 mm², and varying thicknesses and number of layers, ranging from 6.5 mm (5 layer) to 18 mm (13 layers). Two main types of plywood constructions were used: (1) single-species plywood, in which all layers were made from the same wood species, and (2) combination (combi) plywood, where birch was used for the face veneers while black alder or aspen was used in core layers.

Single species plywood was produced to compare the strength of each wood species with that of birch plywood. The combi plywood allowed assessment of the influence of high-quality birch face veneers on the overall strength of plywood made with lower-quality core materials. The specific lay-up schemas are presented in Table 2. Additionally, to evaluate the effect of plywood thickness on bending strength (MOR), plywood panels were prepared in five different thicknesses: 6.5 mm, 9 mm, 12 mm, 15 mm, and 18 mm.

*Table 2. Plywood lay-up schemas (Paper I).*

| **Plywood Type** | **Lay-Up** | **Plywood** |
|---|---|---|
| Birch | I-I-I-I-I-I-I | Standard |
| Black Alder | I-I-I-I-I-I-I | Standard |
| Aspen | I-I-I-I-I-I-I | Standard |
| C-Black Alder | I-I-I-I-I-I-I | Combi |
| C- Aspen | I-I-I-I-I-I-I | Combi |

I -Birch veneer, I -Black alder veneer, I -Aspen veneer, Standard plywood: all layers from same species and C-Combi plywood: one birch veneer on each face and core veneers of another species either black alder or aspen.

Standard plywood: all layers constructed from same wood species and C-Combi plywood: one birch veneer on each face and core veneers of another species either black alder or aspen. In total, 416 samples were prepared for density tests, ad 960 samples were prepared for bending tests.

To evaluate the effect of the densified layers on physical and mechanical properties of multi-layered veneer composites, four additional lay-up schemas were prepared for screw withdrawal and, Brinell hardness tests (Paper II) and for bending tests (Paper III) as shown in Table 3 and Figure 1. The plywood types were categorized as follows: undensified (UN), face veneers densified (FVD), all veneer layers densified (AVD) and undensified thick (UN-T). The UN-T type included 3.0 mm thick undensified face veneers and served as a control sample to assess the influence of face veneer densification, as well as to compare the undensified condition of the same amount of veneer material with its densified counterpart.

All plywood types, with dimensions of 200 x 50 mm², were composed of 7 layers with a nominal thickness of 1.5 mm per layer (except UN-T), resulting in a final plywood thickness of 9 mm after hot pressing. The UN-T plywood included 3.0 mm thick undensified face veneers and served as a control to assess the influence of face veneer densification, allowing for comparison between the undensified and densified conditions using the same amount of veneer material. The use of 3.0 mm thick face veneers increased the total thickness of the UN-T plywood to 12 mm while maintaining the same number of seven layers. Total 27 plywoods were prepared for tests.

*Table 3. Plywood types for assessing densified veneer layer effect.*

| Plywood Type | Code | Lay-Up |
|---|---|---|
| Undensified | UN | $UN^{1.5}$- $UN^{1.5}$ -$UN^{1.5}$ -$UN^{1.5}$-$UN^{1.5}$-$UN^{1.5}$-$UN^{1.5}$ |
| All veneers densified | AVD | $D^{3.0\rightarrow1.5}$- $D^{3.0\rightarrow1.5}$ - $D^{3.0\rightarrow1.5}$ - $D^{3.0\rightarrow1.5}$- $D^{3.0\rightarrow1.5}$- $D^{3.0\rightarrow1.5}$- $D^{3.0\rightarrow1.5}$ |
| Face veneer densified | FVD | $D^{3.0\rightarrow1.5}$- $UN^{1.5}$ -$UN^{1.5}$ -$UN^{1.5}$-$UN^{1.5}$-$UN^{1.5}$- $D^{3.0\rightarrow1.5}$ |
| Undensified-Thick | UN-T | UN-$T^{3.0}$- $UN^{1.5}$ -$UN^{1.5}$ -$UN^{1.5}$-$UN^{1.5}$-$UN^{1.5}$-UN-$T^{3.0}$ |

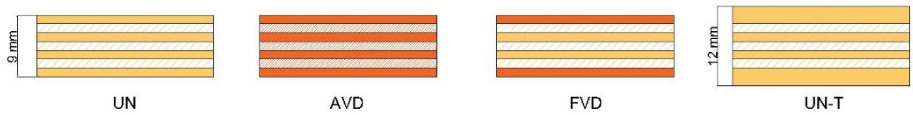


*Figure 1. Plywood lay-up schemas (Colour markings: yellow-undensified veneers and, orange-densified veneers).*

For plywood manufacturing, phenol formaldehyde (PF) resin (Prefere Resins Finland Oy, Hamina, Finland) with a solid content of 49% was used. An adhesive roller (Black Bros 22-D, Mendota, IL, USA) was employed to apply glue at a target spread rate of 160 g/m2 per glue line. However, the actual glue spread rate varied depending on the wood species due to the different surface roughness of veneers. Total applied glue amount was determined by weighing the veneers before and after glue spreading. Subsequently, the plywood panels were hot-pressed at 130 °C for the durations given in Table 4. A pressing pressure of 1.4 MPa was used.

*Table 4. Hot-press pressing times for different plywood thicknesses.*

| Thickness (mm) | Duration (min) |
|---|---|
| 6.5 | 7 |
| 9 | 9 |
| 12 | 11 |
| 15 | 12 |
| 18 | 14 |

## 2.5 Methods

### 2.5.1 Specimen preparation and conditioning

Specimen dimensions were measured according to EN325:2012 after conditioning in a climatic chamber (ILKA KTK800) at 20 ± 2 °C and 65± 5% RH. Thickness was measured in accordance with EN 315:2002.

### 2.5.2 Density determination

The density of plywood samples was measured in accordance to EN323:2002. Specimens were cut into 50 x 50 mm² squares. Specimens were measured after conditioning at 20 ± 2 °C and 65± 5% RH until constant mass. Length, width and thickness were measured with a sliding calliper (accuracy 0.01 mm) and mass was determined using a balance (accuracy 0.001 g). Density was calculated by dividing mass by volume.

### 2.5.3 Bending strength (MOR) and modulus of elasticity (MOE)

Three point bending tests were carried out based on EN310:2002, utilizing a 50 kN universal testing machine (Zwick/Roell Z050, ZwickRoell GmbH, Germany) (see Figure 2). All test specimens were conditioned at 20 ± 2 °C and 65 ± 5% RH for at least 24 hours, as specified in the standard.

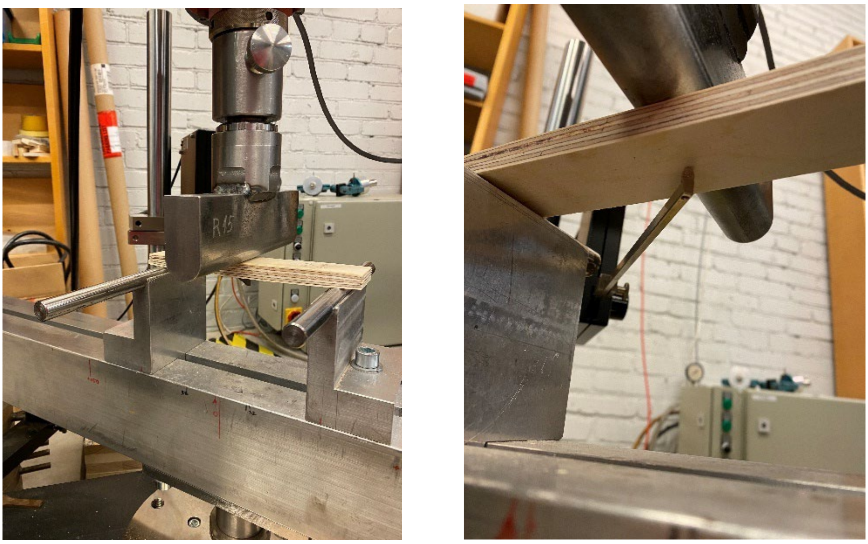


*Figure 2 Bending strength (MOR) and modulus of elasticity (MOE) determinations*

### 2.5.4 Densification ratio determination

The densification ratio (DR) is defined as the percentage increase in density as a result of the densification process. It is calculated by comparing the initial and final densities of the material. The formula (1) for calculating the densification ratio is given as:

$$DR = \frac{(D_f - D_i)}{D_i} \times 100, \qquad (1)$$

where:

$DR$= Densification ratio (%),
$D_f$= Final density after densification (kg/m$^3$),
$D_i$= Initial density before densification (kg/m$^3$).

A higher densification ratio indicates a greater increase in density, which is typically associated with improved mechanical properties such as hardness, bending strength, and surface wear resistance.

### 2.5.5 Compression ratio determination

The compression ratio (CR) measures the reduction in thickness of the material due to applied pressing pressure during densification. It is an essential parameter for understanding the compaction behaviour of wood and is expressed as a percentage decrease in thickness relative to the initial thickness. The formula (2) for calculating the compression ratio is:

$$CR = \frac{(t_i - t_f)}{t_i} \times 100, \qquad (2)$$

where:

$CR$= Compression ratio (%),
$t_i$= Initial thickness before densification (mm),
$t_f$= Final thickness after densification (mm).

The compression ratio provides valuable information about the deformation characteristics of the wood material under varying pressure and moisture content conditions.

### 2.5.6 Effect of moisture content on compression and densification

To ensure consistent comparison, the adjusted compression ratio accounts for changes in initial EMC and is calculated as:

$$CR_{adjusted} = \frac{(t_i - t_{f,adjusted})}{t_i} \times 100, \quad (3)$$

where:

$CR_{adjusted}$ = Adjusted compression ratio (%),

$t_i$ = Initial thickness before densification (mm),

$t_{f,adjusted}$ = Final thickness after conditioning at standard RH (65%) and temperature (20 °C) (mm).

### 2.5.7 Brinell hardness test

The Brinell hardness values of the densified and non-densified plywood samples were determined using the procedures outlined in EN 1534:2020. After conditioning at 20 °C and 65% RH, specimens were indented using a 10 mm diameter hardened steel ball under a 1000 N load for 25 seconds using the universal electro-mechanical testing machine (Zwick/Roell Z050, ZwickRoell GmbH, Germany) (see Figure 3). The diameter of the indentation left in the specimen was measured using a calliper with an accuracy of 0.01 mm. The Brinell hardness number was obtained by dividing the applied load by the area of the indentation. Brinell hardness formula is given as follows (4):

$$BH = \frac{2F}{\pi \times D \times \left(D - \sqrt{D^2 - d^2}\right)}, \quad (4)$$

where:

$BH$ = Brinell Hardness Number,

$F$ = applied load (Newtons, N),

$D$ = diameter of the ball indenter (in mm),

$d$ = diameter of the indentation on the surface (in mm)

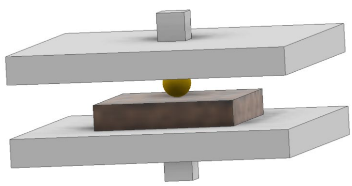

*Figure 3. Brinell hardness test schema*

### 2.5.8 Screw withdrawal strength test

Screw withdrawal strength (SWS) tests were conducted in accordance with EN 13446:2002 using the universal testing machine (Zwick/Roell Z050, ZwickRoell GmbH, Germany). Prior to testing, specimens were conditioned in an environment with a 65%

RH and a temperature of 20 °C until constant mass was achieved. Tests performed from the tangential plywood surface using 4.2x50 mm galvanized wood screws. Cross head loading rate of 2 mm/min was applied until maximum load was achieved. Ultimate withdrawal load was determined and screw withdrawal strength was calculated dividing the ultimate load with radius and penetration depth of the screw (see Figure 4 and Formula (5)).

$$SWS = \frac{F_{max}}{d \times l_p}, \qquad (5)$$

where:

*SWS* = Screw withdrawal strength, MPa
*F* = maximum withdrawal load (Newtons, N)
$l_p$ = depth of penetration of fastener (in mm)
*d* = nominal diameter of the fastener (in mm)

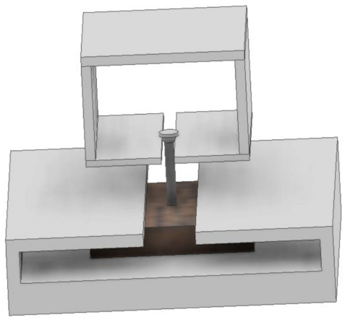

*Figure 4. Screw withdrawal test schema*

### 2.5.9 Statistical data analysis

ANOVA statistical analysis was used to compare the strength properties of non-densified and densified plywood samples, as well as the effects of various lay-up schemes. MS Excel Analysis Tool Pak was used for the data analysis, which was conducted at a 95% confidence level of significance. The significance of the differences was ascertained using the Bonferroni test.

# 3 Results and discussion

## 3.1 Comparison of the physical properties of aspen and black alder composites with birch

### 3.1.1 Effect of veneer densification on composite density

The relationship between wood density and mechanical properties is well-documented across various wood species. These properties, including strength, modulus of elasticity (MoE), and bending strength (MOR), all show a positive correlation with density. The literature highlights that higher wood density generally correlates with improved mechanical properties, confirming that density is a key factor influencing the overall performance and quality of wood(Kollmann et al, 1984, Frederick et al, 1950).

Focusing specifically on the species of common aspen and black alder, which are often classified as low-quality hardwoods due to their relatively low density and thus resulting lower mechanical properties when compared to higher-quality hardwoods. (Kallakas et al., 2020), note that aspen and black alder have not been widely used in plywood production, primarily due to their lower mechanical properties, making them less desirable than more robust species such as birch. Additionally, the several papers acknowledge that lower density correlates with reduced strength and stiffness, limiting the utility of these species in demanding applications (Barbu et al., n.d.; Laine et al., 2016).

The mechanical weaknesses of aspen and black alder can also be traced back to their growth patterns and anatomical structures. Moreover, Kallakas et al. (2020) emphasize that their lower performance metrics contribute to their rejection in favour of higher-quality alternatives, further solidifying their status as suboptimal choices for industrial applications.

In Paper I, the densities of low-quality hardwood species were investigated and compared with birch in multi-layered wood composites. The density values of aspen, black alder, and birch plywood panels were measured and compared in Table 5. Among the three species, birch plywood had the highest overall average density (705 kg/m$^3$), while black alder plywood had the lowest density (583 kg/m$^3$) for seven-layer panels made with 1.5 mm veneers. The use of birch face veneers with lower-density aspen or black alder core layers increased the overall panel density.

For the study (Paper I), plywood panels were prepared in various thicknesses (6.5 mm, 9 mm, 12 mm, 15 mm, and 18 mm) using five different lay-ups, including pure aspen, pure birch, pure black alder, combi aspen, and combi black alder. Different thicknesses were chosen to determine if there is a trend and relationship between the physical and mechanical properties of plywood and its thickness. Density measurements of plywoods were taken after conditioning the specimens at 65±5% relative humidity and 20±2 °C.

The results showed that black alder plywood was the lightest, while birch plywood was the heaviest. Also, aspen and combi aspen plywoods were consistently denser than black alder and combi black alder plywoods across all thicknesses. This difference can be explained by aspen's rougher surface and thus higher glue consumption combined with the glue's density (1.2 kg/L or 1200 kg/m$^3$), which significantly contributed to the overall panel density.

*Table 5. Average densities for various thickness and types of plywood, along with standard deviations in parentheses.*

| Plywood Density, kg/m³ (SD) | | | | | | |
|---|---|---|---|---|---|---|
| **Plywood Type\ Thickness** | **6.5 mm** | **9 mm** | **12 mm** | **15 mm** | **18 mm** | **Overall Average, kg/m³** |
| Aspen | 637 (16) | 643 (13) | 641 (18) | 642 (21) | 650 (14) | 642 (16) |
| Birch | 695 (24) | 702 (50) | 707 (29) | 717 (42) | 704 (18) | 705 (33) |
| B. Alder | 586 (42) | 583 (37) | 584 (41) | 587 (34) | 567 (29) | 581 (36) |
| C-Alder | 615 (36) | 602 (27) | 608 (29) | 600 (28) | 576 (21) | 600 (28) |
| C-Aspen | 608 (46) | 654 (23) | 634 (5) | 662 (10) | 640 (29) | 640 (23) |

After observing in Paper I, that these wood species have lower densities than birch, which leads to lower mechanical properties, densified veneers were incorporated into the lay-up of multi-layered wood composites, primarily in plywood, to enhance their performance. The density variations resulting from this densification process were presented in Paper II, Paper III and Paper IV, showing notable improvements in overall panel density and mechanical strength.

Densification processes significantly enhance wood density, thereby improving mechanical properties essential for structural applications. By compressing the wood structure, densification reduces porosity and increases mass per unit volume. The extent of density augmentation depends on the wood species, initial density, and the densification technique applied.

Experimental results from Paper III, demonstrate the effect of densification in plywood applications. When aspen veneers compressed from 3.0 mm to 1.5 mm and used as face veneers (FVD), the resulting plywood density increased from 603 kg/m³ (UN) to 725 kg/m³, representing a 20.2% increase. In contrast if the same veneer configuration was used without densification (UN-T), the overall panel thickness would increase to 12 mm, leading to a reduced density of 548 kg/m³, a 9.1% decrease compared to UN plywood.

Similarly, black alder plywood with densified face veneers showed a density increase from 676 kg/m³ (UN) to 846 kg/m³ (FVD), a 25.1% rise. Without densification (UN-T), the density dropped to 571 kg/m³, indicating a 15.5% decrease.

When compared to birch plywood, which exhibited an average density of 798 kg/m³, the black alder FVD plywood exceeded this benchmark, emphasizing the potential of densification to elevate lower-density hardwoods to or beyond the performance level of traditionally favoured species like birch.

Furthermore, data from Paper II, indicated applying densified veneers across all layers (AVD) resulted even more significant improvements of the physical properties. For black alder, density increased by 20% with FVD and 31% with AVD relative to UN black alder plywood. For aspen, the corresponding increases were 11% and 28% respectively.

These findings align with previous research indicating that densification enhances wood properties remarkably. For example, poplar wood, initially at 420 kg/m³, can reach 1,207 kg/m³ after chemical pre-treatment and densification—an increase of 187% (Mania et al., 2020). Similarly, birch wood density can be increased from 657 kg/m³ to 1,240 kg/m³ through partial delignification and densification (Mania et al., 2020). The extent of density augmentation is influenced by factors such as the wood species, initial density, and specific densification techniques employed. The application of chemical treatments prior to densification can further amplify density gains. Research indicates that densified wood samples, pre-treated with a combination of sodium hydroxide (NaOH) and sodium sulphite ($Na_2SO_3$), achieved densities exceeding 1,000 kg/m³, representing an increase of over 100% compared to untreated wood (Shi et al., 2020).

These findings confirm that placement of densified veneers-especially when used throughout all layers of plywood construction-can lead to a substantial enhancement in panel density, which in turn supports better mechanical performance in demanding structural applications.

### 3.1.2 Glue consumptions of plywoods made from low quality wood species

Kallakas et al. (2020) indicated that aspen veneers have rougher surfaces than birch and other hardwood species, affecting glue consumption by roller applications in plywood manufacturing. Surface roughness directly influences adhesive performance and quality, with thicker aspen veneers exhibiting more irregularities, which requires additional amount of adhesive for effective bonding.

Bekhta et al. (2014) found that untreated birch veneers have smoother surfaces. Similarly, Meija et al., 2025,noted that aspen veneers showed significantly higher surface roughness than birch also they concluded that increased surface roughness reduces adhesive contact.

In summary, aspen's rougher surface results in higher glue consumption and lower adhesion efficiency, making it less suitable for high-quality plywood applications.

In Paper I, the glue consumption of different plywood types was analysed under identical application conditions and machine settings. The lowest glue consumption was recorded for birch plywood at 152 g/m², while the highest was observed in combi aspen plywood, reaching 187 g/m², as shown in Table 6. Birch, black alder, and combi black alder plywood (which included birch face veneers) exhibited the most similar glue consumption levels.

Aspen plywood consumed 15.8% more glue than the reference birch plywood. In combi plywood, glue consumption followed the pattern of core veneers, where the adhesive was applied. This variation in adhesive usage is attributed to the wood veneer surface characteristics and absorption tendencies of different wood species, significantly influencing overall glue retention in plywood production.

*Table 6. Glue consumptions in comparison of plywoods from different wood species and their combinations*

| Plywood Type | Average Glue Consumption, g/m² |
|---|---|
| Aspen | 177 (±16) |
| Birch | 152 (±7) |
| B. Alder | 156 (±10) |
| C-Alder | 156 (±8) |
| C-Aspen | 187 (±8) |

In the studies presented in Papers II and III, the glue consumption values for each plywood type are provided with standard deviations in parentheses in Table 7. These studies, which examined the effects of densified veneers on the physical and mechanical properties of plywood, also evaluated glue consumption across different plywood types. Among the UN type plywoods, aspen plywood exhibited the highest glue consumption. In contrast, the lowest glue consumption values were recorded for AVD plywoods of black alder and aspen, specifically 133 g/m² for black alder and 136 g/m² for aspen. This reduction in adhesive usage is attributed to the improved surface smoothness resulting from the densification process, as supported by findings in existing literature(Bekhta et al., 2014, 2017).

*Table 7. Glue consumptions of plywoods with densified and undensified veneer layers*

| Wood Species | Plywood Type | Glue Consumption g/m² |
|---|---|---|
| Birch | UN | 160 (±11) |
| Black Alder | UN and UN-T | 165 (±11) |
| | AVD | 133 (±2) |
| | FVD | 160 (±7) |
| Aspen | UN and UN-T | 187 (±21) |
| | AVD | 136 (±7) |
| | FVD | 159 (±19) |

## 3.2 Comparison of the mechanical properties of aspen and black alder multi-layered composites with birch

### 3.2.1 Screw withdrawal and hardness improvement with densification

In the construction, packaging and furniture industries, screws have been increasingly used in the multi layered wood products, making screw withdrawal capacity (SWC) a critical property for ensuring structural performance. At the same time, surface hardness plays a vital role in providing abrasion resistance, durability and visual quality, particularly in applications such as flooring and cabinetry. The densification process not only increases the density of these products but also significantly enhances their surface hardness and SWC, which are critical for applications requiring durability and fastening strength. However, low-density wood species often exhibit insufficient SWC, limiting their use in structural applications. SWC is influenced by several factors, including wood species, density and shear strength.

The influence of wood species on SWC is well documented. (Aytekin, 2008) showed in their tests on oak, stone pine, black pine and fir that oak, with the highest density exhibited the highest SWC. A study on Japanese larch cross laminated timber (CLT) demonstrated that a 50 kg/m³ increase in density led to average 9.4% increase in SWC (Xu et al., 2021). Similarly, the decline in SWC due to reduced density-such as in biodegraded wood-further confirms this direct relationship between density and SWC (Oh, 2021).

Shear strength, which describes the interaction between fibres and the screw, also significantly affects the SWC (Gašparík et al., 2015). Mclain (1997) emphasized that small-diameter fasteners used in low density wood species may require adjustments in design strength assumptions. Consequently, increasing the density of such low-density species through densification has become a prominent research focus to enhance their mechanical performance, particularly in terms of screw withdrawal. Similar trends have been observed in various panel materials, where increases in panel density and cellulose nanofibril addition have corresponded with improved SWC (Leng W., 2017). Moreover, densification has been shown to improve nail withdrawal capacity by up to 200% and SWC by up to 140% (Madhoushi et al., 2010).

This thesis demonstrated that densifying low-value hardwood species, such as aspen and black alder, and incorporating them as face veneers in plywood leads to substantial enhancements in SWC (see Figure 5 and 6). For instance, Paper II showed that densifying face veneers increased SWC by 16% in aspen FVD plywood and by 38% in AVD aspen plywood compared to UN plywood. Similarly, black alder plywood exhibited a 35% improvement with FVD plywood and 50% increase with AVD plywood compared UN plywood. A positive trend was also visible in the addition of more densified veneer layers, particularly in black alder AVD plywood, where the highest SWC (59.38 MPa) was observed. While this value was not significantly higher than that of birch UN plywood (p=0.022), it was nearly equivalent (57.87 MPa).

Another notable observation is that incorporating additional densified layers into black alder plywood lay-up did not substantially enhance SWC, with only 5.74 MPa increase from FVD to AVD, which was not statistically significant(p=0.14). These findings demonstrate the potential for optimizing low-value species like aspen and black alder for demanding structural applications, such as furniture, flooring, and other multi-layered wood composites that require enhanced surface properties and fastener holding strength.

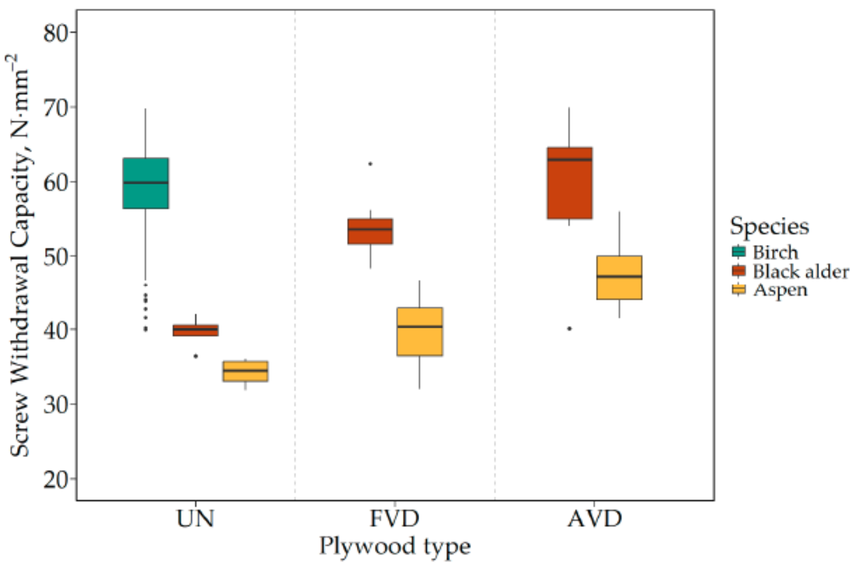


*Figure 5. Average screw withdrawal capacity values for the tested plywood types*

*Figure 6. Screw withdrawal test applied sample*

Surface hardness is another important property for multi-layered veneer-based products- particularly in applications requiring surface abrasion, scratch and impact resistance. It has been shown that the surface hardness of wood significantly increases with the densification process (Sandberg & Navi, 2013). Radial densification also improves hardness across all three anatomical directions (Mania et al., 2022), while surface densification has led to substantial increases in Janka hardness, especially at higher pressing temperatures (Zhou et al., n.d.). This provides a valuable opportunity to enhance the outer layers of veneer-based products, increasing both surface hardness and consequently, screw withdrawal resistance (Goli et al., 2017; Perçin & Altunok, 2019).

As shown in Paper II, using densified veneers in plywood construction significantly affects mechanical properties, particularly surface hardness and screw withdrawal capacity. Veneer densification led to a significant ($p < 0.017$) increase in Brinell hardness (BH) compared to UN plywood (see Figure 7). Specifically, the Brinell hardness of aspen plywood increased by 65%, and black alder plywood by 93%, relative to their UN plywood counterparts. This increase in hardness due to densification has also been reported in previous studies and is attributed to the closing of the vessel and fibre lumens, as well as lathe check conglutination (C.-H. Fang et al., 2012; Kamke, 2006; Navi & Heger, 2004; Student et al., 1993)

The impact of densification on hardness is particularly evident when comparing face-veneers densified plywood (FVD) to UN plywood. Interestingly, no significant increase ($p>0.5$) in Brinell hardness was observed when all layers of plywood were densified (AVD), which could be explained by the fact that hardness testing measures only the surface layer, and deeper layers do not contribute to the measured value.

These results align with previous findings indicating that hardness depends largely on the density of the face veneer and the applied force during measurement. Furthermore, the data showed that densifying low-value wood species like aspen and black alder can raise their surface hardness to levels comparable to, or even higher than, birch UN plywood. Aspen FVD plywood showed similar surface hardness to birch ($p = 0.041$), while AVD samples exhibited slightly higher surface hardness than birch ($p = 0.013$). Black alder FVD and AVD plywood samples had significantly higher surface hardness than undensified birch plywood ($p < 0.017$). Both densified plywood types for these species showed a clear improvement in BH over birch control samples, with only minor differences between FVD and AVD.

Enhancing surface hardness through densification broadens the application potential of low-value wood species, particularly in furniture and flooring applications, where resistance to wear is critical.

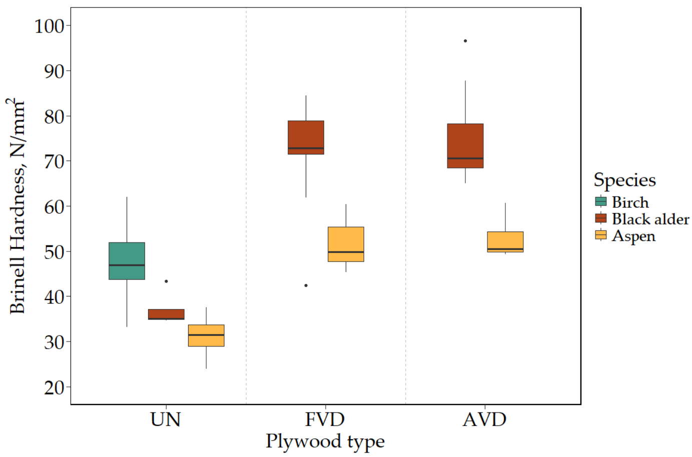


*Figure 7. Average Brinell hardness values for the tested plywood types*

The ability to improve screw holding capacity and surface hardness through veneer densification opens up new possibilities for utilizing lower-density wood species in high-performance applications. This approach helps to optimize material use and expands the range of suitable applications for multi layered wood products.

### 3.2.2 Bending strength and modulus of elasticity (MOE) of multi-layered wood composites

Bending strength is a critical property in multi-layered wood composites, directly influencing their load-bearing capacity and structural integrity. High bending strength ensures that these composites can withstand significant stress and deformation, making them suitable for applications such as flooring, furniture, and structural components. Conversely, lower bending strength may limit their use in load-bearing applications, necessitating careful selection of wood species and lay-up configurations to meet specific performance requirements.

Studies have demonstrated that the bending strength of multi-layered wood composites varies significantly depending on the used wood species. For instance, research comparing beech and aspen laminated wood found out that beech exhibited higher bending strength, approximately 32% greater than aspen (Kúdela & Andor, 2020). Additionally, the arrangement of veneers within the composite plays a crucial role. Combinations such as non-densified and densified veneers (N-D-N) have been shown to influence bending strength, with the highest values observed in non-loaded samples (E.-A. Salca & Bekhta, 2021)

These findings highlight the necessity of optimizing veneer composition and layer arrangement to enhance the mechanical performance of multi-layered wood composites, ensuring their suitability for demanding structural applications.

In Paper I, presented in Figure 8, clear trends were observed in bending strength across different plywood types and thicknesses. As the plywood thickness increased, bending strength decreased in the grain direction and increased in the cross-wise direction, leading to convergence at higher thicknesses. Birch plywood exhibited the highest bending strength across all thicknesses, ranging from 120 MPa at 6.5 mm to 99.1 MPa at 18 mm. Black alder plywood had the lowest values in the grain direction, with reductions of 18.8% at 6.5 mm and 34.7% at 18 mm compared to birch. In the cross direction, birch reached 71.6 MPa at 18 mm, while black alder had the lowest strength, with reductions of 43.4% at 6.5 mm and 31.3% at 18 mm relative to birch.

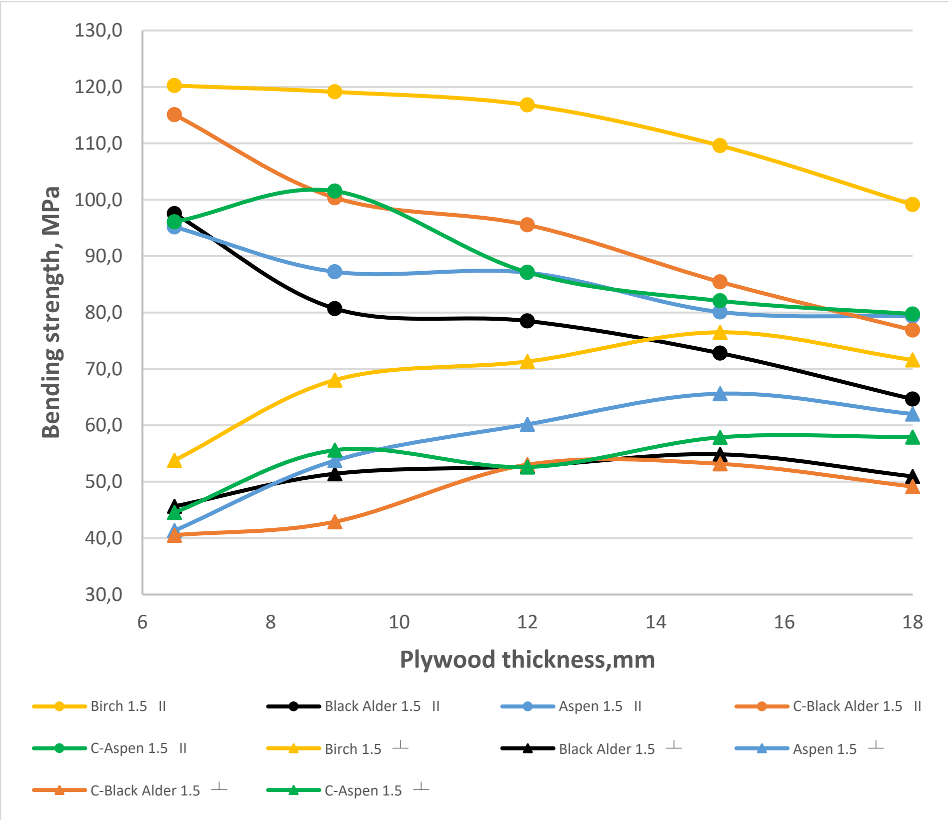


*Figure 8. MOR of different plywood types and thicknesses, in grain (II) and across (┴) the grain direction. (Note: the same colour is used for both in grain and across direction (lower values) for each plywood type).*

Table 8 illustrates the modulus of elasticity (MOE) trends, which followed a similar pattern to bending strength. In the grain direction, aspen showed a 12.1% lower MOE than birch (12,447 MPa), while black alder exhibited a 30.0% reduction. In the cross direction, aspen and black alder had MOE reductions of 26.8% and 28.6%, respectively. Combi black alder plywood demonstrated a 20% higher MOE in the grain direction compared to pure black alder. However, no significant improvement was observed in the cross direction, which is expected since there was no birch veneer layer included in that orientation.

*Table 8. MOE vs thickness for different plywood types and thicknesses, in grain (II) and cross (┴) direction. (Note: the same colour is used for both in grain and cross-wise direction (lower values) for each plywood type).*

| | Plywood MOE, MPa | | | | | |
|---|---|---|---|---|---|---|
| **Plywood Type** | **6.5 mm** | **9 mm** | **12 mm** | **15 mm** | **18 mm** | **Overall Average** |
| **Aspen** | | | | | | |
| II | 12 379 | 11 368 | 10 589 | 9 536 | 10 228 | 10 941 |
| ┴ | 2 220 | 4 865 | 4 639 | 6 781 | 5 670 | 4 541 |
| **Birch** | | | | | | |
| II | 13 490 | 12 803 | 12 637 | 12 545 | 10 775 | 12 447 |
| ┴ | 4 455 | 5 737 | 6 609 | 7 222 | 7 154 | 6 201 |
| **Black Alder** | | | | | | |
| II | 10 236 | 8 552 | 8 679 | 8 408 | 7 613 | 8 708 |
| ┴ | 3 298 | 4 188 | 4 662 | 5 016 | 5 080 | 4 429 |
| **C-Alder** | | | | | | |
| II | 12 893 | 11 863 | 10 829 | 10 446 | 8 804 | 10 985 |
| ┴ | 2 940 | 3 543 | 4 669 | 4 949 | 4 928 | 4 180 |
| **C-Aspen** | | | | | | |
| II | 11 210 | 10 992 | 9 544 | 10 408 | 9 519 | 10 458 |
| ┴ | 3 821 | 5 302 | 5 132 | 6 287 | 6 211 | 5 422 |

Failure mode analysis highlighted material breaking differences between the tested wood species. Black alder exhibited brittle failure, breaking suddenly without warning, whereas aspen demonstrated ductile failure, accompanied by noticeable cracking sounds before ultimate failure, as shown in Figure 9. Ductile failure is generally preferred in structural elements because it provides visible warning signs, such as deformation, before complete failure, allowing for timely intervention and reducing the risk of catastrophic collapse. In contrast, brittle failure occurs abruptly, with little or no prior deformation, making it more hazardous in load-bearing applications (William d. Callister, 2018). Additionally, ductile materials can absorb more energy before failure, enhancing the overall structural resilience, which is particularly important in earthquake-resistant and impact-resistant designs ((Michael F. Ashby, 2012)). Aspen specimens also showed partial recovery of deformation after load removal, indicating superior toughness and energy absorption, making them a more suitable choice for applications where resistance to sudden failure is critical.

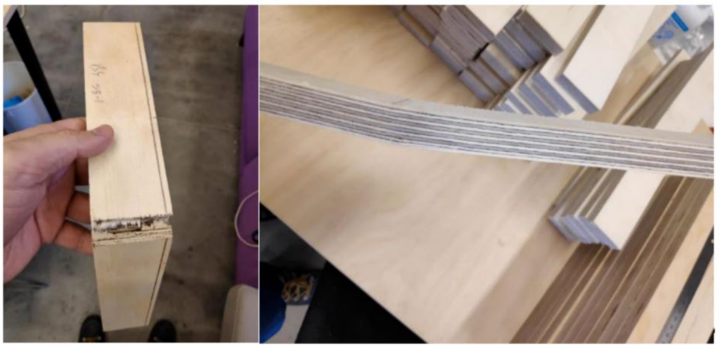

*Figure 9. Test pieces after bending tests, showing brittle failure in black alder (left), and ductile failure in aspen (right) plywood.*

Densification, a process involving the compression of wood veneers under heat and pressure, significantly influences the mechanical properties of plywood, particularly its bending strength. By reducing the porosity and increasing the density of the veneers, densification enhances the interaction between wood fibres, leading to improved load-bearing capacities (Cabral et al., 2022; Kamke, 2006).

Recent research indicate that plywood manufactured from densified veneers exhibits notable improvements in bending strength and MOE peak achieved approximately 13,105 MPa when veneers were densified at 150 °C (E. A. Salca et al., 2020). However, it was observed that further increasing the densification temperature led to a gradual decrease in both MOR and MOE values, suggesting an optimal temperature threshold for the densification process (E. A. Salca et al., 2020).

Furthermore, the arrangement of densified and non-densified veneers within the plywood structure affects its mechanical performance. Plywood configurations that incorporate densified veneers in the outer layers have shown enhanced bending properties (Bekhta et al., 2023). This improvement is attributed to the increased density and stiffness of the outer layers, which bear the majority of the bending stress (Cordier et al., 2025)

However, the densification process also presents certain challenges. Excessive densification can lead to increased brittleness, potentially reducing the material's ability to absorb energy before failure (Cabral et al., 2022). Additionally, higher densification temperatures may degrade hemicelluloses and other wood components, adversely affecting the mechanical properties of the plywood (Rowell et al., 2009).

In Paper III, results it was indicated that using densified veneers on the faces of plywood significantly (FVD) increased bending strength (MOR), modulus of elasticity (MOE), and load-carrying capacity compared to the same thickness (9 mm) of non-densified plywood (UN). However, it should be noted that the total material usage for achieving the same thickness increases. If densified veneers were used without densification (UN-T), the same plywood would be thicker (12 mm) with less bending strength but higher load-carrying capacity. This result aligns with previous research (Perkitny & Jabloński, 1984), suggesting that the load-carrying capacity decreases in compressed elements compared to non-compressed ones. Also, (Avila et al., 2012), demonstrated load-displacement curves for both undensified aspen veneers and densified oil heat-treated aspen samples, which showed that the load-carrying capacity remained similar 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:

$$Stress = \frac{Force}{Area} = \frac{F}{b \times t}, \qquad (6)$$

Where:
$F$ is the load in newtons, b is the width in mm, and t is the thickness in mm.

However, as seen in this formula (6), 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 & Menezzi, 2016, compared densified laminated veneer composites with undensified composites and found a significant increase in compression strength; however, this increase was not proportional to the thickness reduction. Similarly, (Bekhta et al., 2020) compared 20% compressed birch veneer plywood samples to undensified birch plywood samples and found that the increase in strength was not proportional to the reduction in thickness. These results demonstrated 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 tests, strength formulas vary depending on conditions such as test type (3-point or 4-point), support configuration (simply supported, roller supported, cantilever, fixed support etc.), loading type (distributed, point, dynamic), and the load position.

In the case of a 3-point bending test, the stress is calculated according to EN310 using equation (7), which is as follows:

$$Bending\ strength\ (\sigma) = \frac{3\ x\ force\ x\ length}{2\ x\ width\ x\ thickness^2} \qquad (7)$$

This equation (5) shows that bending strength is inversely proportional to the square of thickness. Assuming constant force-carrying capacity and constant sample length and width, reducing the thickness to 0.5 t, should result in a theoretical fourfold increase in strength. However, the literature typically shows only 1.1 to 2.5 times the strength of non-densified samples (Cencin et al., 2021; Han et al., 2022; Namari et al., 2021; Pertuzzatti et al., 2018; Surrel, 2012; Ulker et al., 2012).

Some studies have reported strength increases higher than the theoretical prediction, but they did not provide values of Fmax, making it unclear whether or not load-carrying capacity was reduced. One study demonstrated that subjecting samples to around 20 minutes of pre-treatment at 100 °C resulted in a greater increase than expected by the bending formula calculation (Pertuzzatti et al., 2018).

Several factors should be considered. As thickness decreases after densification, the moment for tension-compression couples shortens. Even if the load carried by the top fibres were doubled, the $t^2$ effect in the denominator diminishes the bending capacity, resulting in lower load carrying capacity. 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 (Avila et al., 2012; C. H. Fang et al., 2011; Han et al., 2022).

Some recent results from literature (Kutnar & Kamke, 2012; Surrel, 2012) examines the relationship between bending strength and wood density to evaluate the benefits of densification relative to changes in material density. This method offers an alternative perspective compared to assessing bending strength alone, particularly in understanding the impact of densification on tensile and bending strength. However, a key consideration that is often overlooked is the non-linear relationship between density and bending strength. This is because of 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 significant change in bending strength after densification(Bekhta, Salca, et al., 2020; E. A. Salca et al., 2020; Scharf et al., 2023; Ulker et al., 2012).

The force exerted in bending can be calculated from equation Eq. (8) as

$$Force = \frac{2\ x\ bending\ strength\ x\ width\ x\ thickness^2}{3\ x\ length} \qquad (8)$$

Considering the equation (6), and making the assumption that the bending strength doubles as a result of densification, the total force ($F_{max}$) carried by the samples would actually be reduced to half compared to undensified sample due to the reduction in thickness. This highlights the importance of not relying solely on bending strength when evaluating structural performance.

As shown in Paper III, densification of veneers led to a reduction in load-carrying capacity, even though bending strength increased. This is a critical finding, as it suggests that thinner, denser veneers may increase strength per unit area but on the contrary it decreases the overall maximum load carrying capacity of the sample.

However, this loss in load carrying capacity can be mitigated by applying more layers and using densified face veneers, which increase the moment arm length and help to maintain load-carrying capacity.

It is also important to note that most literature focuses heavily on bending strength, while $F_{max}$ values- the actual load-bearing capacity- are often overlooked. This gap underscores the need for a more comprehensive approach in future studies (Arruda & Menezzi, 2016; Bekhta, Salca, et al., 2020; C.-H. Fang et al., 2012; Gaff & Gašparík, 2015; Salmen, 1982; Surrel, 2012; Yu et al., 2020).

Thesis analysis confirms that while veneer densification enhances bending strength, it also reduces the total load-carrying capacity of plywood compared to undensified materials. However, for the same 9 mm thickness, densified plywood exhibits increased load-carrying capacity. If plywood thickness is not a constraint, undensified veneers are preferable. Conversely, when dimensional limitations exist, densified veneers offer higher strength within a smaller thickness. Placing densified veneers on the top layers optimizes strength while minimizing load-carrying capacity loss compared to undensified plywood.

When comparing the thickness of undensified and densified plywood samples of the same thickness, densified face veneers result in higher bending strength, modulus of elasticity (MOE), and load-carrying capacity. The advantages and trade-offs of densified plywood depend largely on its intended application.

The same considerations apply to MOE. While MOE increases significantly with densification, it does not increase proportionally with the changes in thickness. According to EN 310, the MOE calculated using the following formula (9):

$$E_m = \frac{l_1^3 \times (F_2 - F_1)}{4 \times b \times t^3(a_2 - a_1)}, \quad (9)$$

Where:

$E$ = Modulus of elasticity (MPa)
$l_1$ = Span between supports (mm)
$F_1$, $F_2$ - are load levels at two points of 0.1 $F_{max}$ and 0.4 $F_{max}$ respectively (N)
$a_1$, $a_2$: are deflections corresponding to loads $F_1$ and $F_2$ (mm)
$b$ = Width of the test specimen (mm)
$h$ = Thickness of the test specimen (mm)

Theoretically, reducing the thickness by half should increase MOE eightfold due to its inverse cubic relation with thickness. However, experimental results showed only a 1.5 to 2-fold increase, indicating a lower-than-expected rise per(Arruda & Menezzi, 2016; Pelit & Emiroglu, 2021; Perkitny & Jabloński, 1984; Pertuzzatti et al., 2018). Paper III further demonstrated that densification negatively impacts load-carrying capacity, resulting in lower-than-expected MOE values.

Additionally, veneer densification introduces challenges such as spring back and set recovery. Spring back effect refers to elastic recovery of densified wood immediately after hot pressing, while set recovery occurs upon exposure of the densified wood to moisture, causing material to regain some of its original thickness. Various methods- including chemical modification, heat, and steam treatments- have been explored to mitigate these effects. However high temperatures may weaken densified wood (C.-H. Fang et al., 2012; Pertuzzatti et al., 2018; Ulker et al., 2012). Some studies suggest that removing lignin and hemicellulose may help reduce set recovery, as these components contribute to shape memory behaviour during densification (Avila et al., 2012; Cencin et al., 2021). However, some research generally shows that undensified samples possess better dimensional stability than densified ones (Arruda & Menezzi, 2016; Bekhta, Salca, et al., 2020).

In summary, veneer densification enhances plywood's bending strength and stiffness, but optimizing parameters such as temperature and compression ratio is crucial to balance strength gains with potential drawbacks. Proper control of these densification parameters allows the production of high-performance plywood for demanding structural applications.

In Paper III, Figure 10 and Figure 11 illustrate the average values for bending strength (MOR), maximum force ($F_{max}$), and modulus of elasticity (MOE) for different plywood types. Figure 10 compares the bending strength and $F_{max}$ values.

Several key trends emerge from the results. Among the undensified veneer-based plywood control samples (UN), birch plywood exhibited the highest bending strength ($\sigma$ = 123 MPa) and $F_{max}$ (1437 N), while aspen plywood had the lowest ($\sigma$ = 82.7 MPa, $F_{max}$ = 946 N). The use of densified face veneers significantly improved bending strength, with FVD aspen plywood showing a 26% increase compared to UN aspen plywood. The effect was higher for black alder, which exhibited a 38% increase. When comparing UN-T plywood ($\sigma$ = 83.6 MPa and 82.9 MPa for aspen and black alder, respectively) to FVD plywood (σ = 126.3 MPa and 104.6 MPa for black alder and aspen, respectively), it becomes clear that densified face veneers substantially enhanced bending strength while reducing load-carrying capacity. Type FVD had $F_{max}$ values of 1627 N (black alder) and 1189 N (aspen), whereas UN-T type showed 1930 N and 1549 N, respectively. These findings align with previous research, suggesting that compressed wood carries less load than undensified wood of equivalent thickness (Bekhta et al., 2009).

Overall, FVD type plywoods exhibited the highest bending strength, whereas UN-T type plywoods had the highest $F_{max}$. While densification increases both bending strength and $F_{max}$ compared to UN type, it significantly reduces load-carrying capacity when compared to the thicker undensified UN-T type plywood (12 mm). Comparing FVD black alder plywood to UN birch plywood, black alder exhibited slightly higher bending strength, though the difference was not statistically significant. However, both $F_{max}$ and MOE were significantly higher for FVD black alder compared to UN birch plywood.

MOE results (Figure 11) followed a similar trend. Aspen FVD plywood with 3.0 mm densified face veneers exhibited MOE values of 15.8 GPa and 17.3 GPa, respectively, compared to 12.0 GPa for 9 mm UN aspen plywood. Likewise, black alder FVD plywood with 3.0 mm densified face veneers reached 17.7 GPa, compared to 12.0 GPa for undensified black alder plywood. Notably, FVD black alder plywood had an 11% higher MOE than UN type birch plywood (16.0 GPa).

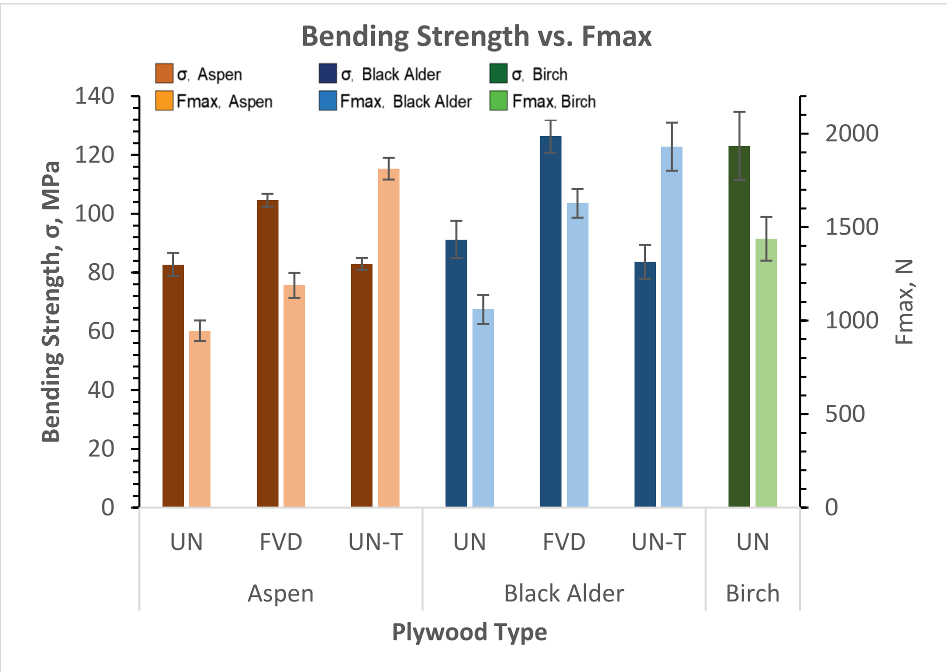


*Figure 10. Bending strength results compared to maximum force carrying capacity (in MPa) for 7-layer plywood. UN-undensified, FVD-face veneers densified, AVD-all veneers densified, UN-T-undensified thick*

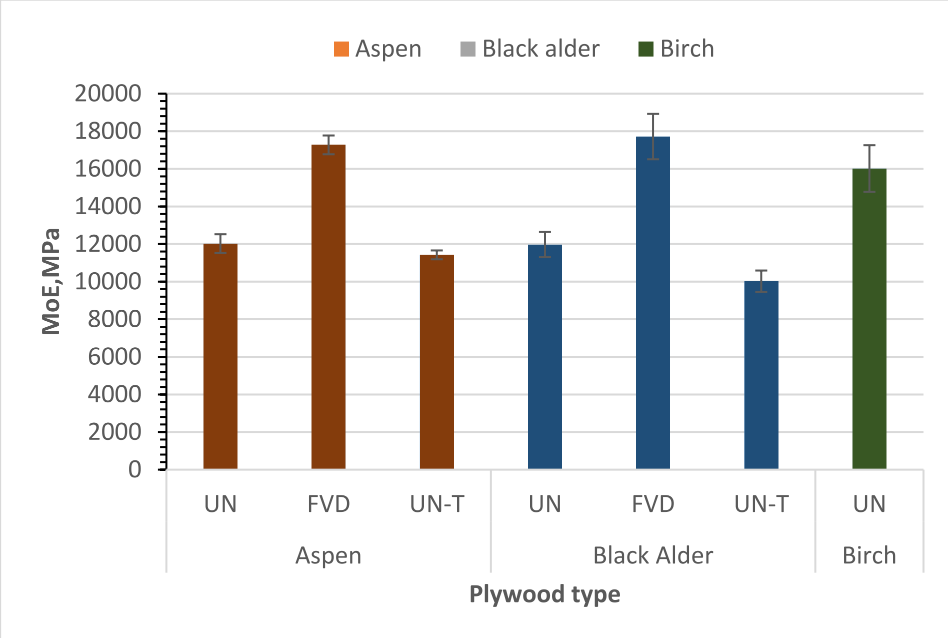


*Figure 11. Modulus of elasticity results (in MPa) for 7-layer plywood. UN-undensified, FVD-face veneers densified, AVD-all veneers densified, UN-T-undensified thick*

## 3.3 Determination of densification parameters to improve physical and mechanical properties of multi layered wood composites

Low quality hardwoods such as aspen and black alder can be effectively utilized in multi layered wood composites—either alone or in combination with high-quality species like birch (Paper I)—further studies have shown that the addition of densified veneer layers significantly improves physical and mechanical properties (Papers II and III). However, the extent of property enhancement through densification is highly dependent on the process conditions applied during treatment. To fully exploit the benefits of densified veneers and ensure their consistent integration into high-performance multi-layered wood products, it is essential to identify and optimize key process parameters.

Pressing temperature, pressing pressure and equilibrium moisture content (EMC) each parameter plays a critical role in determining the final density, compression ratio, and set recovery of the material. Moderate temperatures promote the thermal softening of lignin and hemicellulose without causing degradation, while appropriate pressing pressures ensure sufficient cell wall collapse for mechanical strengthening. Likewise, initial EMC influences both the plasticization of wood and efficiency of heat transfer during densification. Inadequate control of these parameters can result in suboptimal compaction, spring back, or dimensional instability, limiting the mechanical performance and long-term usability of multi layered wood product. Therefore, the following section aims to systematically evaluate the influence of these three factors on veneer densification, providing a basis for selecting optimal processing conditions. The goal is to develop a densification regime that balances mechanical performance with dimensional stability and energy efficiency, enabling

broader industrial application of low-quality hardwood species in structural multi layered wood products manufacturing.
The densification results of the samples under varying temperatures, pressures, and equilibrium moisture contents (EMC) are summarized in
Table 9. Initial and final densities were analysed to evaluate the impact of densification parameters on compaction efficiency.

Densification significantly increased density across all conditions. The highest final density, 1028 kg/m³, was achieved at 90 °C, 5.4 MPa, and 20% EMC, while the lowest, 565 kg/m³, occurred at 170 °C, 1.8 MPa, and 5% EMC. The second-highest final density, 954 kg/m³, was recorded at 210 °C, 5.4 MPa, and 20% EMC. This suggests that at lower temperatures, sufficient moisture facilitates densification, potentially due to the softening effect of water within the wood matrix. Interestingly, at 20% EMC, 90 °C samples densified more under all pressures (1.8 MPa, 3.6 MPa, and 5.4 MPa) than 210 °C, whereas at lower EMC levels, 210 °C yielded higher compaction levels than 90 °C.

The effect of temperature on densification followed expected trends. While increasing temperature generally improved density, lower temperatures combined with higher EMC also led to significant densification. At 90 °C, densification efficiency was high even at lower pressures due to minimal moisture loss, maintaining wood plasticity. At 130 °C and 170 °C, efficiency declined as substantial moisture loss reduced plasticization, leading to lower densities. For example, at 130 °C and 3.6 MPa, EMC dropped from 10.5% to 2.4%, while at 170 °C and 1.8 MPa, EMC decreased from 12% to 0.4%, limiting compressibility (see Table 10).

*Table 9. Veneer densification results under varying temperatures, pressures, and equilibrium moisture content (EMC) values in parentheses show the standard deviations*

| **Temperature** | **5% EMC** | | **12% EMC** | | **20% EMC** | |
|---|---|---|---|---|---|---|
| **Pressure** | **Initial Density, kg/m³** | **Final Density, kg/m³** | **Initial Density, kg/m³** | **Final Density, kg/m³** | **Initial Density, kg/m³** | **Final Density, kg/m³** |
| **90 °C** | | | | | | |
| 1.8 MPa | 551 (49) | 572 (45) | 562 (46) | 598 (42) | 583 (57) | 751 (36) |
| 3.6 MPa | 562 (52) | 607 (42) | 564 (56) | 687 (48) | 583 (51) | 948 (82) |
| 5.4 MPa | 541 (45) | 624 (31) | 563 (51) | 900 (50) | 567 (71) | 1028 (77) |
| **130 °C** | | | | | | |
| 1.8 MPa | 564 (49) | 582 (45) | 580 (51) | 593 (43) | 582 (44) | 617 (23) |
| 3.6 MPa | 557 (56) | 601 (52) | 571 (54) | 621 (49) | 583 (60) | 652 (52) |
| 5.4 MPa | 549 (46) | 635 (25) | 574 (55) | 699 (36) | 584 (58) | 728 (14) |
| **170 °C** | | | | | | |
| 1.8 MPa | 544 (36) | 565 (44) | 562 (50) | 579 (37) | 571 (45) | 589 (42) |
| 3.6 MPa | 563 (58) | 604 (51) | 547 (63) | 603 (45) | 591 (51) | 620 (39) |
| 5.4 MPa | 563 (40) | 644 (18) | 561 (44) | 671 (17) | 590 (54) | 679 (21) |
| **210 °C** | | | | | | |
| 1.8 MPa | 557 (50) | 622 (45) | 569 (42) | 621 (25) | 585 (44) | 628 (21) |
| 3.6 MPa | 562 (60) | 764 (35) | 564 (76) | 767 (21) | 573 (51) | 800 (37) |
| 5.4 MPa | 562 (54) | 941 (31) | 549 (44) | 940 (50) | 589 (48) | 954 (36) |

Densification efficiency improved at 210 °C, despite near-total moisture loss (e.g., from 11.6% to 0.2% at 3.6 MPa). This can be attributed to lignin surpassing its glass transition temperature, enabling structural rearrangement that compensates for moisture depletion. Consequently, 210 °C yielded high densification, particularly at lower EMC levels.

Overall, the highest densification occurred at 90 °C, 5.4 MPa, and 20% EMC, and at 210 °C, 5.4 MPa across all EMC levels. Intermediate temperatures (130 °C and 170 °C) were less effective due to excessive moisture loss reducing plasticization. Higher EMC levels (12% and 20%) generally resulted in greater densification across all conditions. Additionally, increasing pressure from 1.8 MPa to 5.4 MPa consistently enhanced final density. At 90 °C with 20% EMC, density increased from 751 kg/m³ at 1.8 MPa to 1028 kg/m³ at 5.4 MPa. Similarly, at 210 °C with 20% EMC, density rose from 628 kg/m³ at 1.8 MPa to 954 kg/m³ at 5.4 MPa.

These findings highlight the effectiveness of combining high pressure, sufficient EMC, and moderate to high temperatures for optimal densification.

*Table 10. EMC change under different conditions during densification.*

| **Temperature** | **5% EMC** | | **12% EMC** | | **20% EMC** | |
|---|---|---|---|---|---|---|
| **Pressure** | **Initial EMC, kg/m³** | **Final EMC, kg/m³** | **Initial EMC, kg/m³** | **Final EMC, kg/m³** | **Initial EMC, kg/m³** | **Final EMC, kg/m³** |
| **90 °C** | | | | | | |
| 1.8 MPa | 5.2% | 4.6% | 9.6% | 9.1% | 17.9% | 16.5% |
| 3.6 MPa | 5.0% | 4.5% | 9.3% | 9.1% | 17.8% | 16.6% |
| 5.4 MPa | 5.0% | 4.5% | 9.9% | 9.5% | 17.5% | 16.6% |
| **130 °C** | | | | | | |
| 1.8 MPa | 5.0% | 2.2% | 11.8% | 2.6% | 17.8% | 2.6% |
| 3.6 MPa | 4.9% | 2.5% | 10.5% | 2.4% | 17.6% | 2.6% |
| 5.4 MPa | 4.8% | 2.3% | 10.3% | 2.5% | 17.6% | 2.6% |
| **170 °C** | | | | | | |
| 1.8 MPa | 5.4% | 0.7% | 12.0% | 0.4% | 17.2% | 0.8% |
| 3.6 MPa | 5.0% | 0.7% | 11.6% | 0.6% | 17.3% | 0.8% |
| 5.4 MPa | 5.0% | 0.7% | 10.6% | 0.6% | 17.6% | 0.6% |
| **210 °C** | | | | | | |
| 1.8 MPa | 5.9% | 0.3% | 11.8% | 0.3% | 17.5% | 0.5% |
| 3.6 MPa | 5.8% | 0.4% | 11.6% | 0.2% | 17.6% | 0.2% |
| 5.4 MPa | 5.9% | 0.3% | 11.7% | 0.2% | 17.7% | 0.3% |

### 3.3.1 Densification ratio analysis

The densification ratio analysis supports the findings presented in the previous section regarding the influence of pressing temperature, pressure and initial EMC on densification behaviour. At 90 °C, densification ratios were highest at 20% EMC, with a densification ratio reaching 84.4% at 5.4 MPa (Figure 12). This indicates that higher initial moisture content enhances the compressibility of the veneer at lower temperatures, likely due to the improved plasticization of wood matrix. At intermediate temperatures of 130 °C and 170 °C, the densification ratio values were generally lower, reflecting the diminished densification efficiency caused by rapid and excessive moisture loss during pressing. For example, at 130 °C and 5.4 MPa, the densification ratio for 12% EMC was 22.8%, whereas at 90 °C 5.4 MPa, it reached a densification ratio of 61.1%. The sharp reduction in densification efficiency at these mid-range temperatures is attributed to limited plastic deformation due to reduced moisture content.

Densification efficiency improved at 210 °C, despite near-total moisture loss (e.g., from 11.6% to 0.2% at 3.6 MPa). This can be attributed to lignin surpassing its glass transition temperature, enabling structural rearrangement that compensates for moisture depletion. Consequently, 210 °C yielded high densification, particularly at lower EMC levels.

Overall, the highest densification occurred at 90 °C, 5.4 MPa, and 20% EMC, and at 210 °C, 5.4 MPa across all EMC levels. Intermediate temperatures (130 °C and 170 °C) were less effective due to excessive moisture loss reducing plasticization. Higher EMC levels (12% and 20%) generally resulted in greater densification across all conditions. Additionally, increasing pressure from 1.8 MPa to 5.4 MPa consistently enhanced final density. At 90 °C with 20% EMC, density increased from 751 kg/m³ at 1.8 MPa to 1028 kg/m³ at 5.4 MPa. Similarly, at 210 °C with 20% EMC, density rose from 628 kg/m³ at 1.8 MPa to 954 kg/m³ at 5.4 MPa.

These findings highlight the effectiveness of combining high pressure, sufficient EMC, and moderate to high temperatures for optimal densification.
Table 10) and incomplete thermal softening of wood polymers.

At 210 °C, especially at higher pressures densification ratios increased, with the highest densification ratio of 72.4% recorded at 5.4 MPa and 12% EMC. The increase in densification at this temperature is attributed to the thermal softening of lignin and hemicellulose, which facilitates deformation even under very low initial EMC conditions. However, veneer densification at 90 °C and 5.4 MPa, especially at higher initial EMC, achieved even greater densification (up to 84.4%), highlighting the effectiveness of moisture-assisted compaction at lower temperatures.

Comparing the veneer densification results at pressing temperatures of 90 °C and 210 °C at different pressing pressures, it is evident that both conditions yield higher densification values. However, considering industrial mass production efficiency and the feasibility of the densification process and environmental sustainability, the 90 °C pressing temperature is more suitable. The reduced energy consumption at this temperature makes it a preferable option for large-scale densification processes.

To sum it up, while high pressing temperatures of 210 °C enable significant densification even with moisture depletion, densification at 90 °C provides a more balanced approach, offering sufficient densification while maintaining sustainability and industrial.

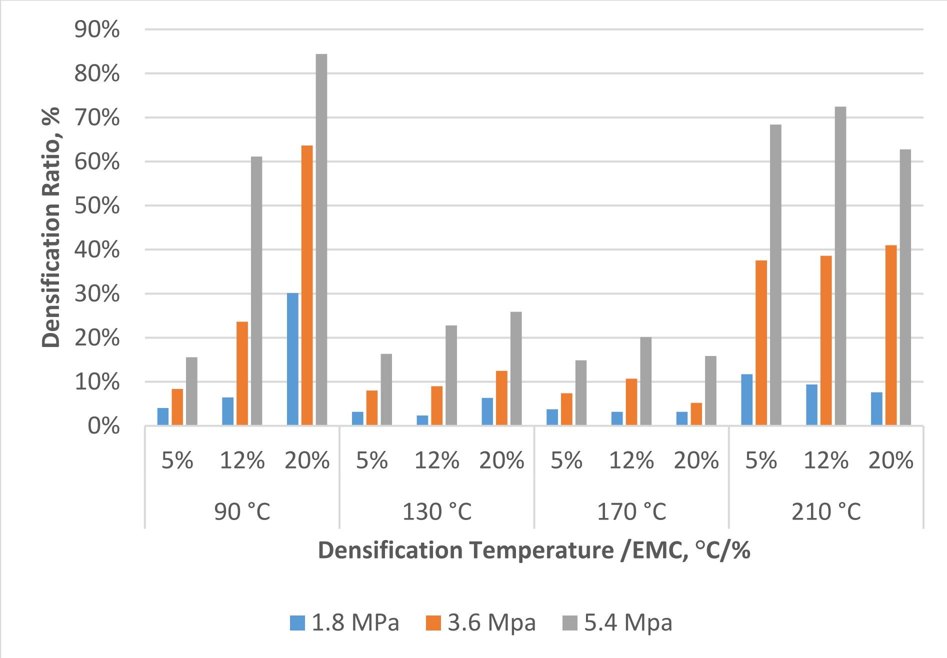


*Figure 12. Densification ratio of samples in various pressing temperature, pressing pressure and initial EMC conditions*

### 3.3.2 Compression ratio analysis

The compression ratio, defined as the percentage reduction in thickness during densification, was evaluated across different processing conditions, including pressing temperature, pressure, and initial equilibrium moisture content (EMC). Figure 13 presents the compression ratios calculated using veneer thickness measured immediately before densification process (at the corresponding initial EMC) and immediately after the densification process. In contrast, Figure 14 presents adjusted compression ratios where the initial thickness is standardized based on the equilibrium thickness of each sample at 65% RH and 20 °C and this reference is then compared to the post-densification thickness. This dual approach enables a more comprehensive assessment of compression behaviour by accounting for both actual in process-material state and standardized environmental conditions for comparison.

Compression ratio trends clearly indicate that both increased pressing pressure and elevated temperature enhance compressibility. At 90 °C, the compression ratios of veneer ranged from 4.4% at 1.8 MPa and 5% EMC to 46.2% at 5.4 MPa and 20% EMC. Similarly, at 210 °C, the compression ratio reached a maximum of 47.5% at 5.4 MPa and 20% EMC, with a minimum of 15.1% at 1.8 MPa and 5% EMC (Figure 13). The substantial increase in densification at elevated temperatures is likely due to the increased plasticity of the wood matrix, particularly above the glass transition temperature of lignin, facilitating greater deformation under pressure.

The effect of initial EMC on compression ratio was also found to be significant. Higher initial EMC values, particularly 20%, consistently led to greater compression ratios, reinforcing the role of moisture as an internal plasticizer that facilitates fibre deformation. In contrast, veneers with lower initial EMC values (5%) exhibited markedly lower compression ratios. This effect was particularly evident at intermediate temperatures (130 °C and 170 °C), where rapid moisture loss diminished wood plasticity and reduced compression efficiency. In comparison, lower temperature densification at 90 °C retained more internal moisture, enabling higher compression under comparable conditions.

Figure 14 provides compression ratios adjusted for uniform equilibrium moisture conditions (65% RH and 20 °C). The adjustments indicate slightly higher compression ratios in most cases compared to the directly measured values in Figure 13. The difference in compression ratios is more pronounced at higher temperatures, particularly at 210 °C, where the adjusted compression ratios reached 48.4% at 5.4 MPa and 20% EMC.

Although the densification parameters 210 °C and 5.4 MPa yielded the highest compression ratios, an important consideration for industrial applications is the balance between densification efficiency, energy consumption, and material sustainability. Comparing the veneer densification results at 90 °C and 210 °C, it is evident that compression ratios at 90 °C under high pressure (5.4 MPa) approach the compression ratio results obtained at 210 °C, particularly at higher EMC levels (Figure 14). Given the significantly lower energy input required at 90 °C, this condition presents a more favourable balance for mass production. Lower densification temperatures reduce wood veneer strength reduction by possible thermal degradation risk, minimize emissions, and decrease operational costs, making them more suitable for industrial-scale sustainable densification processes.

Furthermore, the difference in compression ratios between 90 °C and 210 °C is more pronounced at lower EMC levels, as the gap in compression ratios is significantly wider at lower EMC values. This indicates that the impact of EMC on densification is more substantial at lower temperatures. Additionally, results from 210 °C showed that there is minimal variation in compression ratio across different EMC levels, suggesting that at this temperature, pressing pressure plays a more dominant role in densification compared to EMC. Conversely, at 90 °C, the effect of EMC is more pronounced than the effect of pressure, highlighting the moisture-dependent nature of compression at lower processing temperatures.

These results provide further insight into optimizing densification parameters by identifying processing conditions that deliver high compression with minimal energy input, thereby enhancing feasibility of incorporating low-density hardwoods such as aspen and black alder into high-performance multi layered wood products.

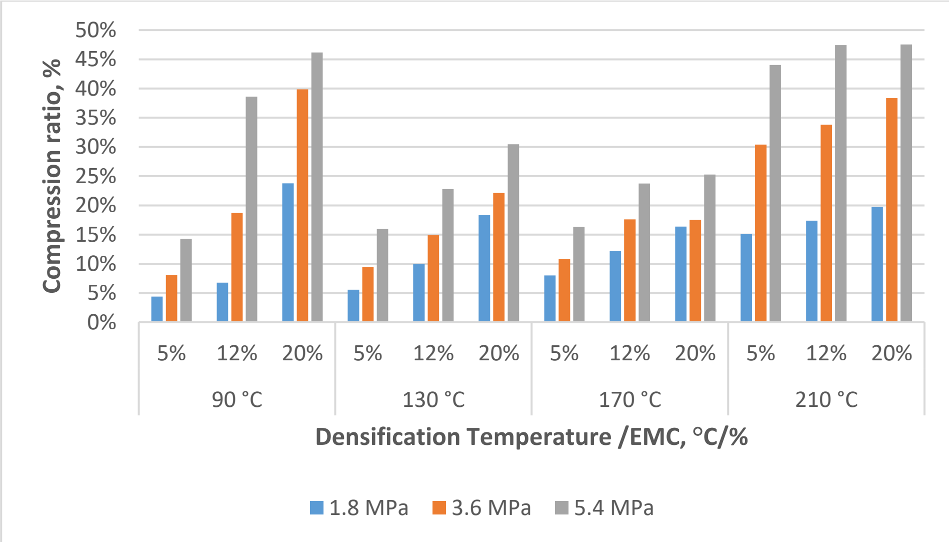


*Figure 13. Compression ratios of samples in various pressing temperature, pressing pressure and initial EMC conditions*

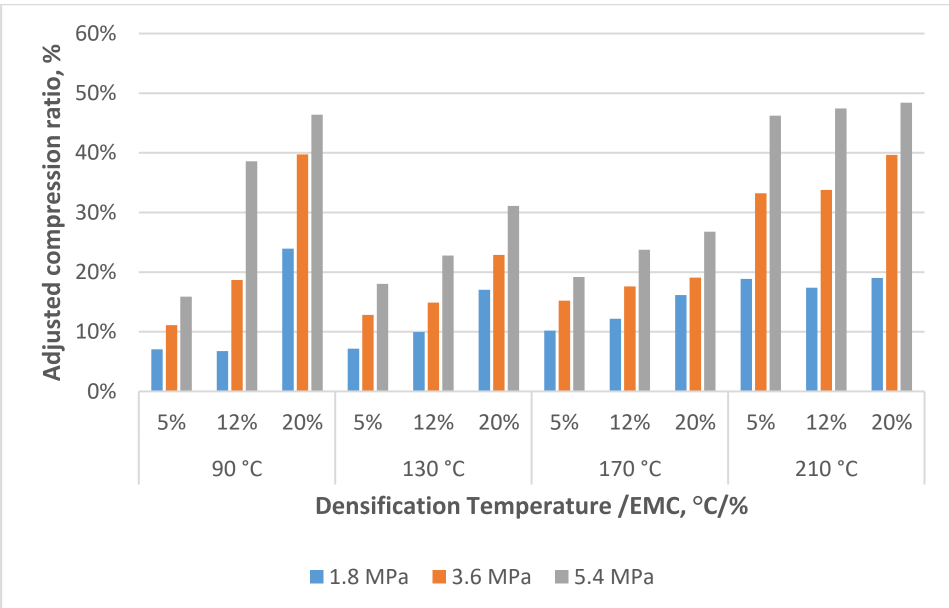


*Figure 14. Adjusted compression ratios of samples in various pressing temperature, pressing pressure and initial EMC conditions*

### 3.3.3 Set recovery effect

Set recovery in densified wood refers to the extent to which the compressed material returns to its original thickness when reconditioned in initial or determined wood storage conditions. A closely related phenomenon, spring back, occurs immediately after pressing pressure release, as the wood attempts to regain its original shape due to the relaxation of internal stresses. While set recovery is evaluated after exposure to humid conditions over time, spring back is typically observed as an instant thickness rebound once external pressure is removed.

In this study, set recovery was evaluated after veneer densification by placing all densified samples into standard conditions of 65% relative humidity (RH) and 20 °C, ensuring consistency in the evaluation process, as the initial EMC values varied across samples during densification. However, due to the nature of the densification process and the equipment used, determining the immediate post-densification thickness was challenging. Since the densification process was conducted without mechanical stoppers, the samples were compressed freely until reaching their final thickness under the applied pressing temperature, sample EMC, and pressing pressure conditions.

All tested samples exhibited some degree of set recovery after reconditioning, regardless of pressing temperature. Among the tested densification conditions, the lowest set recovery was observed at 90 °C, 20% EMC, and 1.8 MPa, indicating that samples densified under these conditions retained more of their compressed state after reconditioning. However, it is important to consider the effect of EMC change between post-densification and reconditioning at 65% RH and 20 °C. For instance, samples densified at 90 °C, 20% EMC, and 5.4 MPa experienced an EMC change from 16.6% to 12% (ΔEMC=4.6%), whereas those densified at 210 °C, 20% EMC, and 5.4 MPa, EMC changed from 0.4% to 12% (ΔEMC=11.6%). If the set recovery values were adjusted proportionally to the moisture change, the differences between these temperatures would likely be less pronounced.

When focusing on the highest compression ratios, which were achieved at 5.4 MPa and 20% EMC, the comparison between two pressing temperatures applied 90 °C and 210 °C revealed that set recovery was lower in 90 °C densified samples (Figure 15). Despite achieving similarly high compression ratios, the samples densified at 90 °C retained more of their reduced thickness after reconditioning compared to those processed at 210 °C. This suggests that densification at high EMC and lower pressing temperatures may contribute to better long-term dimensional stability in thickness retention.

These research findings highlight the influence of pressing temperature, initial EMC, and pressing pressure on the post-densification behaviour of wood. Although set recovery is often considered a major challenge in densified wood applications (Kutnar & Kamke, 2012; Navi & Sandberg, 2012), it should be noted that swelling behaviour is also a significant issue in natural, non-densified wood under fluctuating humidity conditions. This suggests that controlling moisture-related dimensional stability remains a key factor in both natural and densified wood applications.

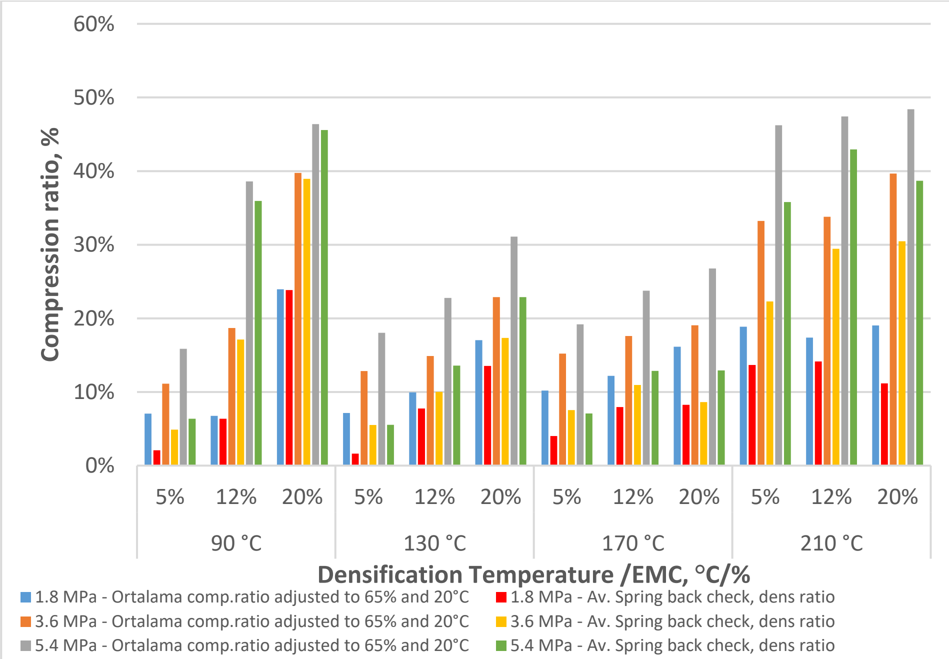


*Figure 15. Compression ratios and comparison between immediately after densification and after conditioned on standard 65%RH and 20 °C*

# 4 Conclusions

This research demonstrates that aspen and black alder can serve as viable alternatives to birch in multi-layered wood composites. By strategically selecting the placement and lay-up of densified veneers, plywood strength comparable to birch can be achieved while utilizing lower-quality hardwood species. The findings of the research suggest that densification is most effective at lower temperatures and can be optimized for enhanced mechanical properties without excessive material use.

Aspen and black alder plywoods exhibited lower bending strength compared to birch plywood. However, these plywoods were also significantly lighter, making them attractive for applications where weight reduction is a priority. By selectively densifying surface veneers, the bending strength of black alder plywood was shown to reach levels comparable to birch plywood while offering a 13% higher load-carrying capacity for the same thickness. This demonstrates that plywood production can be optimized to achieve high strength properties using lower-value wood species.

The study also highlights that densification of all layers is unnecessary for improved performance. Instead, placing densified veneers at the outer layers effectively enhances bending strength, stiffness, and surface hardness while maintaining material efficiency. This selective densification strategy allows for high-performance plywood with reduced glue consumption and better resource utilization.

Key findings from this research include:

- Densifying low-value wood veneers significantly increases plywood density and mechanical properties, with black alder achieving a higher density than birch plywood when densified.
- A strong positive correlation ($r = 0.776$, $p < 0.05$) was observed between plywood density and screw withdrawal capacity. Surface densification significantly improves this property without requiring full densification of all plywood layers.
- The surface hardness of plywood is directly influenced by the density of the face veneer layer, while the density of inner layers does not significantly contribute to surface hardness.
- Densified veneers showed lower surface roughness without negatively affecting bonding quality.
- Plywoods made entirely of densified veneers used more material but did not achieve proportional strength increases compared to selectively densified plywoods.
- Thicker veneers resulted in lower glue consumption and provided comparable strength under one-dimensional loading conditions, making them suitable for specific structural applications.

The veneer densification parameters study revealed that hot pressing at 90 °C with 20% equilibrium moisture content (EMC) and 5.4 MPa pressure resulted in the highest densification ratio of 84.4%. Lower temperatures allowed for efficient densification while maintaining sustainability and industrial applicability. Higher temperatures (e.g., 210 °C) facilitated densification through thermal softening of lignin and hemicellulose, but excessive moisture loss reduced efficiency at intermediate temperatures (130–170 °C).

Overall, this research underscores that by carefully selecting densification parameters and optimizing veneer lay-up, it is possible to produce high-strength, lightweight plywood from lower-quality hardwood species. This strategy not only enhances material efficiency but also offers an economically viable alternative to birch plywood, expanding the potential of multi-layered wood products in industrial applications.

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# Abstract

# Valorizing low-quality wood species into innovative multilayer engineered wood products

Plywood is a widely used engineered wood product consisting of multiple layers of wood veneers bonded together with adhesives under heat and pressure, with the layers arranged in alternating directions. This layered structure enhances its strength, stability, and resistance to warping, making it suitable for various structural and decorative applications. In Estonia, plywood production is almost exclusively based on birch due to its superior mechanical properties and uniform texture. However, birch is predominantly used for face veneers, leading to a scarcity of birch logs and high prices, which makes it necessary to explore alternative hardwood species for plywood production.

The increasing demand for high-quality plywood necessitates exploring alternative hardwood species to reduce reliance on premium birch while maintaining structural performance. Aspen and black alder, traditionally considered lower-value species due to their lower density and mechanical properties, were investigated as potential substitutes for birch in plywood production. Additionally, thermo-mechanical densification was examined as a method to enhance their mechanical and surface properties. This study aims to explore the use of lower-quality hardwood species in veneer-based engineered wood products as an alternative to birch plywood, applying veneer densification techniques to improve strength and surface properties, followed by optimization of the plywood thickness through careful lay-up selection. This study integrates multiple research objectives, including material substitution, the impact of densification on mechanical and surface properties, and the optimization of densification parameters to maximize plywood performance.

Results showed that substituting birch with aspen and black alder in plywood production is viable, particularly when veneer thickness and lay-up configurations are optimized. While veneer densification improved bending strength of plywood significantly, a reduction in load-carrying capacity was observed due to the decrease in plywood thickness, that lowered the material’s moment of inertia. Utilizing densified aspen and black alder veneers in plywood production also resulted in enhanced surface hardness and improved screw withdrawal capacity. This highlights the need for strategic placement of densified veneers within the plywood layered structure to maximize strength while minimizing the reduction of load carrying capacity. To further refine the veneer densification process, an extensive parameter optimization study was conducted, evaluating equilibrium moisture content (EMC), temperature, hot pressing pressure, and pressing duration. The research findings demonstrated that higher initial wood veneer EMC and higher pressing pressure levels (5.4 MPa) resulted in greater veneer densification, especially with two optimal pressing temperature conditions: 90 °C and 210 °C. The 90 °C condition proved to be the most practical for industrial applications due to its energy efficiency and ease of implementation, while 210 °C provided enhanced densification effects but it should be considered this high temperature can cause excessive thermal degradation of wood cell structure.

This research presents a comprehensive approach to improving plywood performance by integrating lower quality hardwoods as a substitution for birch, densification techniques, and process optimization. The research findings contribute

to more sustainable plywood production by enabling the use of lower-cost hardwoods, reducing dependency on birch, and refining densification techniques for future applications. Moving forward, the optimized densification parameters identified in this study should be adapted for aspen and black alder veneers to develop plywood with enhanced mechanical and durability properties, broadening its application potential in the construction and manufacturing industries. These findings can also be used to develop higher-quality plywood from other high-quality wood species like birch, further expanding the potential applications of densified plywood.

# Lühikokkuvõte
## Madalakvaliteediliste puiduliikide puidu väärindamine innovatiivseteks kihilisteks inseneripuittoodeteks

Ristvineer on laialdaselt kasutatav inseneripuittoode, mis koosneb mitmest puiduspooni kihist, mis on kuumpressi all liimliitega kokku liimitud ning kihid on paigutatud ristiasetsevalt. Selline kihiline struktuur suurendab vineeri tugevust, stabiilsust ja deformatsioonikindlust, muutes selle sobivaks mitmesugusteks konstruktsioonilisteks ja dekoratiivseteks rakendusteks. Eestis toodetakse vineeri peaaegu eranditult kasespoonist tänu selle suurepärastele mehaanilistele omadustele ja ühtlasele tekstuurile. Kasespooni kasutatakse aga peamiselt pealisspoonina, mis põhjustab kasepalkide nappuse ja kõrged puidu hinnad, mistõttu on vaja uurida vineeri tootmiseks alternatiivseid lehtpuuliike.

Kasvav nõudlus kvaliteetse vineeri järele tingib vajaduse uurida alternatiivseid lehtpuiduliike, et vähendada sõltuvust kvaliteetsest kasepuidust, säilitades samal ajal vineeri konstruktsioonilise tugevuse. Kase võimaliku asendajatena vineeri tootmisel uuriti haava ja sanglepa kasutusvõimalusi. Haaba ja sangleppa peetakse tavapäraselt madalama tiheduse ja mehaaniliste omaduste tõttu madalama väärtusega puiduliikideks. Lisaks uuriti spooni termomehaanilist tihendamist kui meetodit nende mehaaniliste ja pinnaomaduste parandamiseks. Selle uuringu eesmärgiks oli uurida madalama kvaliteediga lehtpuiduliikide kasutamist spoonipõhistes töödeldud puittoodetes kasevineeri alternatiivina, rakendades spooni tihendamise tehnikaid tugevuse ja pinnaomaduste parandamiseks, millele järgneb vineeri paksuse optimeerimine hoolika spoonikihtide valiku abil. See uuring ühendab mitu uurimiseesmärki, sealhulgas materjali asendamine, tihendamise mõju mehaanilistele ja pinnaomadustele ning tihendusparameetrite optimeerimine vineeri toimivuse maksimeerimiseks.

Uuringutulemused näitasid, et kasespooni asendamine haava ja sanglepaga vineeritootmises on teostatav, eriti kui optimeerida spoonipaksust ja ladumisviisi. Kuigi spooni tihendamine parandas oluliselt vineeri paindetugevust, täheldati vineeri paksuse vähenemise tõttu kandevõime vähenemist ja vineeri inertsimomendi vähenemist. Tihendatud haava- ja sanglepaspoonide kasutamine vineeritootmises suurendas ka spoonipinna kõvadust ja parandas kruvide väljatõmbetugevust. See rõhutab vajadust tihendatud spoonide strateegilise paigutamise järele vineeri kihilisse struktuuri, et maksimeerida tugevust ja minimeerida kandevõime vähenemist. Spooni tihendamise protsessi edasiseks täiustamiseks viidi läbi ulatuslik protsessi parameetrite optimeerimise uuring, milles hinnati tasakaaluniiskuse (EMC), temperatuuri, kuumpressimise rõhu ja pressimise ajalise kestvuse mõju. Uurimistulemused näitasid, et kõrgem algne puiduspooni tasakaaluniiskus ja suurem pressimisrõhk (5,4 MPa) võimaldasid saavutada suurema spooni tihendamise kahe optimaalse pressimistemperatuuri korral 90 °C ja 210 °C. 90 °C temperatuur osutus tööstuslikes rakendustes kõige praktilisemaks oma energiatõhususe ja rakendamise lihtsuse tõttu, samas kui 210 °C pakkus paremat spooni tihendamisefekti, kuid tuleb arvestada, et kõrge tihendamise temperatuur võib põhjustada puidurakkude struktuuri liigset termilist lagunemist.

See uuring esitles terviklikku lähenemisviisi vineeri omaduste parandamiseks, integreerides kase asemel madalama kvaliteediga lehtpuitu, spooni tihendustehnikaid ja protsessi parameetrite optimeerimist. Uurimistulemused aitavad kaasa

jätkusuutlikumale vineeritootmisele, võimaldades kasutada odavamaid lehtpuiduliike, vähendades sõltuvust kasest ja täiustades spooni tihendustehnikaid tulevaste rakenduste jaoks. Edaspidi tuleks käesolevas uuringus tuvastatud optimeeritud tihendusparameetreid kohandada haava- ja sanglepa spoonide jaoks, et arendada välja vineeri, millel on paremad mehaanilised ja vastupidavusomadused, laiendades selle rakenduspotentsiaali ehituses, transpordis ja muudes rakendustes. Uurimistöö tulemusi saab kasutada ka kvaliteetsema vineeri tootmiseks kõrgekvaliteetsetest puiduliikidest, näiteks kasest, laiendades veelgi tihendatud spooniga kaetud vineeri potentsiaalseid rakendusalasid.

# Appendix 1

**Publication I**

Akkurt, T.; Kallakas, H.; Rohumaa, A.; Hunt, C. G.; Kers, J. (2022). Impact of Aspen and Black Alder Substitution in Birch Plywood. Forests, 13 (2), 142.

*forests*

*Article*

# Impact of Aspen and Black Alder Substitution in Birch Plywood

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**Abstract:** Increasing demand pressures on the fibre supply are forcing manufacturers to explore using new species in plywood. Here we investigated aspen and black alder, alone and in combination with birch faces, and with different veneer thicknesses in plywood production. The aim of this study was to evaluate the effect of different veneer thicknesses, lay-up systems, and hardwood veneer combinations on plywood mechanical properties. Impacts on modulus of rupture (MOR), modulus of elasticity (MOE), glue consumption, and density properties were observed. All process parameters were the same as for pure birch plywood. Not surprisingly, birch plywood had the highest MOR and MOE, followed by aspen and black alder. Aspen had the highest glue consumption and birch the lowest, when applied with a spreader roll, but the common practice of using relatively thick 2.6 mm aspen veneers resulted in the lowest glue consumption per mm of product. The effects of wood species and veneer thickness on MOR, density, and glue consumption were analysed for panel thicknesses from 6.5 to 18 mm to guide manufacturers in choosing their species and construction to optimize cost, MOR and stiffness, weight, and glue consumption. In conclusion, birch gave the best strength properties while aspen gave the best price and weight combination.

**Keywords:** plywood; aspen; birch; black alder; bending strength; lay-up



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## 1. Introduction

Plywood is the second highest volume wood panel product in the world [1]. In Estonia, timber and wood-based products are one of the biggest contributors to the economy, accounting for 10% of gross domestic product (GDP) and 5% of the workforce. In the Baltic and Nordic regions of Europe, silver birch is the most common species in plywood production. About 51% of Estonian territory is covered by forest, of which 29.9% is birch, 4% is aspen and 2.2% is black alder, the species investigated here [2]. The main wood species utilised by plywood manufacturers in Northern Europe are spruce, pine, and birch. These species have been used for many decades due to the availability and high quality of the wood material. However, climate change and efficient utilisation of biomass, e.g., low-quality wood species, will drive the veneer-based product industry to seek out other sources and species. Aspen and black alder are not commonly used in the production of plywood, either as sole-species or mixed-species products. In the past, their relatively lower availability and quality compared to birch made their utilisation not feasible. Moreover, these species have commonly lower density [3], and lower density has been shown to decrease the mechanical properties of wood [4]. However, these species have lower log prices, and especially for aspen, lower density provides the possibility of lower cost and lower weight products.

Utilisation of hardwood species by the veneer-based industry has been described by [5] in an extended literature review. However, in that review, the focus was on North

American, Asian, and Australian hardwood species and on laminated veneer lumber (LVL). More recent research has been focused also on aspen and black and grey alder species. Rohumaa et al. [6] showed that these species could be successfully bonded and combined with each other under current plywood manufacturing conditions. Moreover, Kallakas et al. [7] showed that birch, aspen, and alder species could be combined by different lay-up systems in order to manipulate the strength properties of the final product. Previous studies also show that veneers from different wood species have different roughness, even if they are prepared under the same conditions [6]. In order to form a successful bondline, the contact between the surfaces should be sufficient and overcome the roughness [8]. Commonly, in the case of rough veneer, the plywood manufacturers increase the adhesive spread rate and press pressure, but the effectiveness of this technique has not been confirmed [9]. The reason could be related to veneer processing conditions [10–13], which also affect lathe check formation. Commonly, thicker veneer has deeper lathe checks [13], which affect the adhesive consumption [14] and bonding quality of the plywood [12]. However, previous research on aspen and alder veneers did not evaluate the effect of veneer thickness and adhesive consumption on plywood mechanical properties.

Therefore, the goal of this study was to evaluate the effect of different veneer thicknesses, lay-up systems, and hardwood veneer combinations on plywood mechanical properties.

## 2. Materials and Methods

### *2.1. Wood Species and Lay-Up Schemas for Plywood*

In this research, veneers from three different wood species were used for plywood production: birch (*Betula pendula* Roth), black alder (*Alnus glutinosa* L.), and aspen (*Populus tremula* L.). The logs were freshly felled in September 2020 from Käru, Rapla County in Estonia by State Forest Management Centre (RMK). Mean stand age was 76 years, and logs had quality class B and C [15]. The log nominal lengths were 3 m, and average diameters were 24 cm (birch), 26 cm (black alder), and 33 cm (aspen). The logs were visually sorted and those with less knots, no crooked body, and no decay were chosen for veneer production.

Birch, black alder, and aspen veneers had nominal thickness of 1.5 mm, and aspen veneers were also made with nominal thickness of 2.6 mm to obtain better surface quality for softer wood species. Plywood lay-up schemes were constructed using standard cross-band construction as either single species (Standard) or as birch face veneers with aspen or black alder in the core (Combi). In total, seven plywood types were prepared, four of which were from only one species and three combinations. Single species plywood was produced to compare its strength with birch plywood, and combination plywood was produced to observe the effect of face veneers on total plywood strength. Lay-up schemes are described in Table 1. Additionally, to observe the effect of plywood thickness on MOR, plywood with five different thicknesses was prepared: 6.5 mm, 9 mm, 12 mm, 15 mm, and 18 mm.

**Table 1.** Plywood lay-up schemas (last number of plywood type indicates veneer thickness in mm).

| Plywood Type | Lay-Up | Plywood | Face Veneer Thickness (mm) | Core Veneer Thickness (mm) |
|---|---|---|---|---|
| Birch 1.5 | **I-I-I-I-I** | Standard | 1.5 | 1.5 |
| Black Alder 1.5 | I-I-I-I-I | Standard | 1.5 | 1.5 |
| Aspen 1.5 | I-I-I-I-I | Standard | 1.5 | 1.5 |
| Aspen 2.6 | **I-I-I-I-I** | Standard | 1.5 | 2.6 |
| C-black alder 1.5 | **I**-I-I-I-**I** | Combi | 1.5 | 1.5 |
| C-aspen 1.5 | **I**-I-I-I-**I** | Combi | 1.5 | 1.5 |
| C-aspen 2.6 | **I-I-I-I-I** | Combi | 1.5 | 2.6 |

I—Aspen 1.5 mm veneer, **I**—Birch 1.5 mm veneer, I—Black Alder 1.5 mm veneer, I—Aspen 2.6 mm veneer. Standard—single wood species. Combi—one birch veneer on each face and core veneers of another species.

### *2.2. Veneer and Plywood Manufacturing Process*

Logs were cut to peeler block length of 1200–1400 mm and kept totally immersed in a water tank for 24 h at 40 °C. After 1 day of soaking, logs were debarked by hand and larger surface knots removed. Before peeling, the following properties were recorded: temperature and moisture content in the outer face and in the core, diameter, log length, heartwood width, and sapwood width. Then, the logs were peeled at 60 rpm with a Raute peeling lathe (Model 3HV66; Raute Oyj, Lahti, Finland) with knife angle of 21° and compression rate of 10%. In total, 36 blocks were peeled into veneer: 9 aspen, 14 black alder, and 10 birch were peeled to 1.5 mm veneers, and 3 peeler blocks of aspen were peeled at 2.6 mm. Veneers were then sorted for defects and knots and graded visually for face and core use. As in industry, the veneers with large knots were placed in cores, as the core has much less impact on product quality than faces. The veneer mat was first cut by hydraulic guillotine to 450 × 900 $mm^2$ for drying and later, dried veneers were cut to 450 × 450 $mm^2$ for plywood production. The veneers were dried at 170 °C to reach a target moisture content of 4.5 ± 1.5% in a laboratory scale veneer dryer (Raute Oyj, Lahti, Finland), where humidity inside the dryer was 500–600 g/kg.

Since all species have different properties, the drying time for each species and veneer thickness varied. Veneers were stored in Laboratory of Wood Technology, Tallinn University of Technology, Tallinn, Estonia storage room at 25 °C and 20% relative humidity (RH) to maintain target moisture content (4 to 5%).

Phenol formaldehyde (PF) resin (Prefere Resins Finland Oy, Hamina, Finland) with solid content of 49% was used. A glue roller (adhesive roller Black Bros 22-D) was used to apply glue at a target spread rate of 160 g/$m^2$ per glue line. Total applied glue was calculated by weighing the veneers before and after spreading. Panels were hot-pressed at 130 °C for the times given in Table 2. Pressing pressure was 1.4 MPa based on preliminary trials. The number of panels (in total 144) for each combination and thickness is given in Table 3.

**Table 2.** Hot-press times for different plywood thicknesses.

| Thickness (mm) | Time (min) |
|---|---|
| 6.5 | 7 |
| 9 | 9 |
| 12 | 11 |
| 15 | 12 |

**Table 3.** Number of plywood panels produced.

| Plywood Thickness, mm | Birch | Black Alder | Aspen | Aspen 2.6 mm | Combi 1.5 mm (Aspen or Black Alder) | Combi 2.6 mm (Aspen) |
|---|---|---|---|---|---|---|
| 6.5 | 4 | 4 | 4 | 4 | 8 | |
| 9.0 | 4 | 4 | 4 | | 8 | 4 |
| 12.0 | 4 | 4 | 4 | 4 | 8 | |
| 15.0 | 4 | 4 | 4 | | 8 | 4 |
| 18.0 | 8 | 8 | 8 | 8 | 16 | |
| Total | 24 | 24 | 24 | 16 | 48 | 8 |

### *2.3. Standards and Methods of Analysis*

Specimen dimensions were measured according to European Standard EN325:2012 [16] after conditioning at 20 ± 2 °C and 65 ± 5% RH in the climatic chamber (ILKA KTK800). Thickness was measured according to EN315:2002 [17]. Some samples of aspen plywood with 2.6 mm aspen veneers were over-compressed, and were near, but less than, the lower limit specified by the standard. Density was determined according to EN323:2002 [18]. For each plywood panel six 50 × 50 mm specimens were prepared, except for 12 mm and 15 mm plywoods, where only four samples were prepared because of limited material. The total number of prepared density samples, therefore, was 624. All densities were measured after conditioning of specimens in relative humidity of 65 ± 5% and 20 ± 2 °C to reach constant weight with two successive measurements.

Mechanical properties were evaluated with a three-point bending test according to EN310:2002 [19], using a the 50 kN universal testing machine (Zwick/Roell Z050, Zwick-Roell GmbH, Germany). All test specimens were conditioned at 20 ± 2 °C, 65 ± 5% RH for at least 24 h as specified in the standard. Forty-eight specimens for every thickness for every type of plywood were tested to give a total of 1440 test samples. Linear correlations for glue consumption vs. MOR were based on the standard Pearson's method, where each pure species plywood type was analysed separately, as implemented in the Microsoft Excel data analysis toolkit regression function.

## 3. Results

### 3.1. Glue Consumption and Density

Glue was applied to all veneers under the same conditions and with the same machine settings. The lowest glue consumption was 152 g/m$^2$ with birch plywood, and the highest was 196 g/m$^2$ with aspen containing 2.6 mm veneers, as shown in Table 4.

**Table 4.** Glue consumption per glue line (last number shows veneer thickness in mm).

| Plywood Type | Average Glue Consumption (g/m$^2$) | Standard Deviation (g/m$^2$) |
|---|---|---|
| Birch 1.5 | 152 | 7 |
| Black Alder 1.5 | 156 | 10 |
| Aspen 1.5 | 177 | 16 |
| Aspen 2.6 | 195 | 7 |
| C-Black Alder 1.5 | 156 | 8 |
| C-Aspen 1.5 | 187 | 8 |
| C-Aspen 2.6 | 185 | 6 |

Birch, black alder, and combi black alder plywood (which has birch face veneers) had the most similar glue consumption. Aspen 1.5 mm veneer consumed 15.8% more glue than the reference birch, while 2.6 mm aspen veneer consumed 28.3% more. For combi plywood, glue consumption followed the pattern of core veneers, where adhesive was applied.

As shown in Figure 1, total glue consumption at a given thickness was highest for combi aspen and aspen 1.5 mm veneer plywood. Black alder, combi alder, and birch plywood were very similar to each other. The lowest glue consumption was with 2.6 mm aspen plywood and 2.6 mm aspen combi plywood, with 34%–40% lower consumption compared to birch and close to 50% less than 1.5 mm veneer aspen or combi-aspen plywood.

Panel densities are given in Figure 2. Birch plywood had the highest density (707 kg/m$^3$) while black alder plywood had the lowest of those made with 1.5 mm veneers (583 kg/m$^3$). As expected, using birch face veneers with lower density cores increased average panel density. Aspen 2.6 mm veneers produced plywood panels with significantly lower density than those with 1.5 mm veneers, including the lowest density plywood panels in the study, aspen 2.6 mm at 549 kg/m$^3$.

### 3.2. Bending Strength (MOR) and Modulus of Elasticity (MOE)

Several trends in MOR are apparent in Figure 3. First, as panel thickness increased, MOR in the grain direction decreased and increased in the cross direction. As a result, the MOR in the grain and cross direction started to converge at the high thicknesses. The highest MOR was observed in pure birch plywood using 1.5 mm veneers at all thicknesses (from 120 N/mm$^2$ for 6.5 mm to 99.1 N/mm$^2$ for 18 mm) and lowest in the plywood with only black alder 1.5 mm veneers (from 97.5 N/mm$^2$ for 6.5 mm to 64.7 N/mm$^2$ for 18 mm). In the cross direction, birch plywood had the highest MOR for all thicknesses (from 53.8 N/mm$^2$ for 6.5 mm to 71.6 N/mm$^2$ for 18 mm), and aspen plywood with 2.6 mm veneers had the lowest (from 20.6 N/mm$^2$ for 6.5 mm to 45.9 N/mm$^2$ for 18 mm).

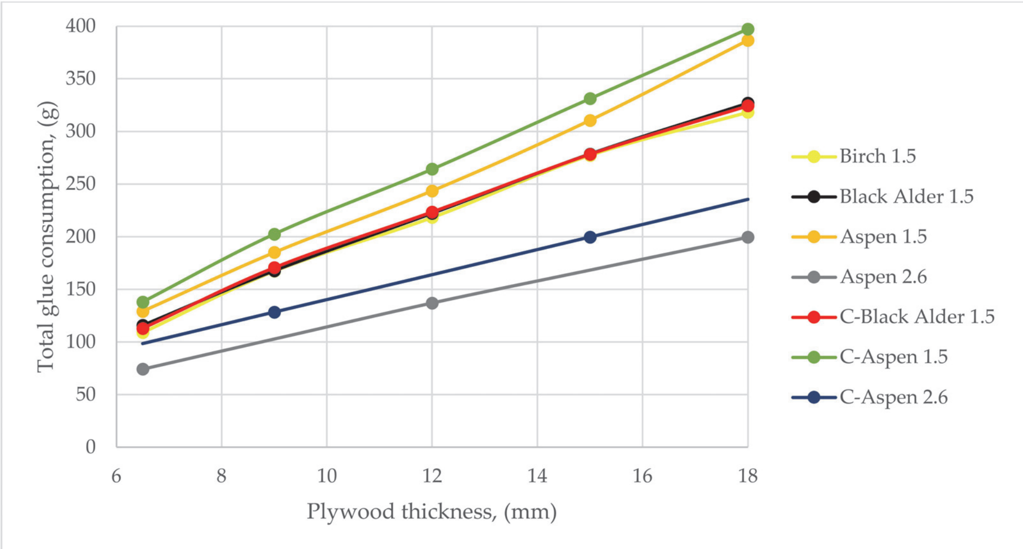


**Figure 1.** Total glue consumption per panel vs. plywood thickness for all plywood types. (Last number shows veneer thickness in mm).

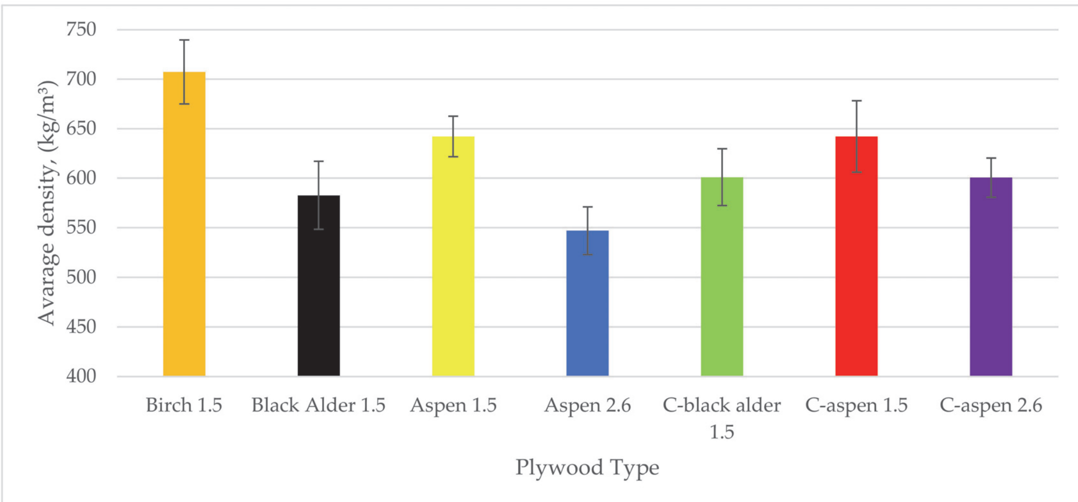


**Figure 2.** Average densities according to plywood type (lines on bars show standard deviations).

When comparing MOR, all plywood panels showed lower strength than birch, as summarized in Table 5. The lowest relative (and absolute) strength was for 6.5 mm plywood from 2.6 mm pure aspen in the cross direction, because this panel contains only one cross veneer, placed at the neutral axis.

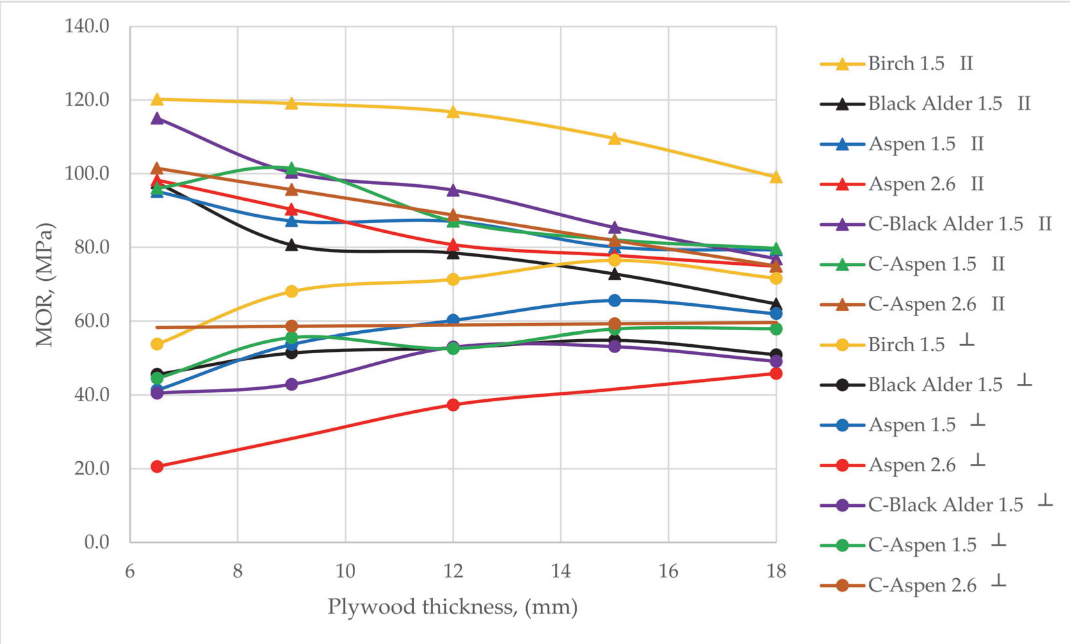


**Figure 3.** For different plywood types and thicknesses, MOR vs. thickness, in grain (II) and cross (⊥) direction. (Note: the same colour is used for both in grain and cross direction (lower values) for each plywood type).

**Table 5.** Strength decrease relative to standard birch plywood at each thickness.

| Plywood Thickness | Grain Direction | | | | | | Cross Direction | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | B. Alder | Aspen | | C-Alder | C-Aspen | | B. Alder | Aspen | | C-Alder | C-Aspen | |
| | 1.5 | 1.5 | 2.6 | 1.5 | 1.5 | 2.6 | 1.5 | 1.5 | 2.6 | 1.5 | 1.5 | 2.6 |
| 6.5 | −19% | −21% | −18% | −4% | −20% | | −15% | −23% | −62% | −25% | −17% | |
| 9 | −32% | −27% | | −16% | −15% | −20% | −24% | −21% | | −37% | −18% | −14% |
| 12 | −33% | −25% | −31% | −18% | −25% | | −26% | −16% | −48% | −26% | −26% | |
| 15 | −34% | −27% | | −22% | −25% | −25% | −28% | −14% | | −30% | −24% | −22% |
| 18 | −35% | −20% | −24% | −22% | −20% | | −29% | −13% | −36% | −31% | −19% | |
| Average | −30% | −24% | −24% | −16% | −21% | −23% | −25% | −17% | −49% | −30% | −21% | −18% |

For MOE, all results followed the same pattern as MOR. With increasing thickness, MOE decreased in the grain direction and increased in the cross direction. In the grain direction, average MOE results for all thicknesses included were 10,737 N/mm$^2$ for aspen, 12,447 N/mm$^2$ for birch, 8707 N/mm$^2$ for black alder, and in cross direction, average MOE results for all thicknesses included were 5490 N/mm$^2$ for aspen, 6201 N/mm$^2$ for birch, and 4429 N/mm$^2$ for black alder. For aspen plywood with 2.6 mm veneers, MOE was 11,270 N/mm$^2$ in the grain direction and 3013 N/mm$^2$ in the cross direction. In MOE, results were not significantly different for combi aspen and aspen plywood panels, but combi black alder plywood gave higher results (10,985 N/mm$^2$) in the grain direction, while there was no significant change in the cross direction (4180 N/mm$^2$).

The correlation between glue consumption and MOR varied from very weak (0.05) in birch to a moderate 0.58 in combi black alder, as can be seen from Table 6. However, only the combi black alder correlation was strong enough to be statistically significant ($p < 0.05$), even though most sets had 24 data points.

**Table 6.** Glue consumption—MOR correlation coefficients.

| Plywood Type | Correlation Coefficient | $2/\sqrt{n}$ |
|---|---|---|
| Birch 1.5 mm | 0.05 | 0.41 |
| Black Alder 1.5 mm | 0.14 | 0.50 |
| Aspen 1.5 mm | 0.10 | 0.41 |
| Aspen 2.6 mm | 0.26 | 0.41 |
| C-Black Alder 1.5 mm | 0.58 | 0.41 |
| C-Aspen 1.5 mm | 0.27 | 0.41 |
| C-Aspen 2.6 mm | −0.52 | 0.71 |

## 4. Discussion

During pressing, aspen plywood samples compressed more than those made of the other two wood species, resulting in lower final thicknesses. Some plywood samples designed at 18 mm thickness were only 14.5 mm thick when using 2.6 mm thick aspen veneer. This is a result of using the same pressing parameters for all wood species and combinations in the study, rather than tailoring conditions for each wood species. Lower density wood species such as aspen typically compress more [7]. This resulted in higher density aspen plywood.

Glue was applied to the veneers with glue spreading rollers; this caused glue consumption variations by species and veneer thickness as expected. Glue consumption was higher for aspen veneers compared to black alder and birch veneers. As is typical for aspen, it had a much rougher, fuzzier surface than the other species, which is often associated with higher glue uptake from glue spreading rollers [7], whereas the veneers from two other wood species were smooth. Aspen 2.6 mm thick veneers consumed 28% more glue than birch and black alder veneers or 1.5 mm aspen veneers. The thicker veneers had rougher surfaces and more warpage than thin veneers; this is also supported by other researchers' work [13]. Combi aspen plywoods with 2.6 mm veneers had higher densities than black alder and combi alder plywoods, even though they had less total glue consumption than the plywood made with 1.5 mm veneers of different wood species. The 2.6 mm aspen veneers compressed more than black alder veneers, resulting in lower final thickness of the plywood. Moreover, aspen plywoods with 1.5 mm veneers had higher glue consumption per glue line and more glue per panel. Higher glue consumption contributed to higher density in aspen plywood made with 1.5 mm veneers compared to black alder plywood produced with 1.5 mm veneers, since glue has higher density than veneers. Aspen plywoods with 2.6 mm veneers were 15 to 22% lighter than birch plywoods of the same thickness. A curtain or extrusion application system would likely do a better job of keeping constant spread rates, allowing better comparison of results without considering total glue consumption.

We found that for six of the seven panel types, glue consumption had no correlation ($p > 0.05$) to MOR. There does appear to be a correlation in combi black alder, suggesting that more resin may be needed on this species. As PF resin is known to stiffen and strengthen wood adjacent to the glue line through cell wall penetration, some amount of reinforcement from additional adhesive is expected [20]. However, the lack of a significant correlation suggests that the glue spread rate did not influence strength properties in most panels. The proper spread rate needs to be determined for each species and process.

Another question to address is whether the birch face plies on combi boards provided any benefit. In the grain direction, combi black alder was 20% stronger than pure black alder, and some improvement was also seen in combi-aspen 2.6 plywoods relative to pure aspen 2.6. There was little difference between aspen 1.5 and combi-aspen 1.5. In the cross direction, the combi aspen plywoods had better MOR than pure aspen, while combi-black alder was not improved over pure black alder.

For 2.6 mm pure aspen plywood, the lowest MOR value in the cross direction was obtained with 6.5 mm panel, which was 62% lower than that for birch. This is an expected result because this plywood has just one cross layer located on the neutral axis. Clearly, this would have a strong detrimental impact on MOR. Even at the higher thicknesses, 2.6 mm aspen MOR in the cross direction was notably lower than that of 1.5 mm aspen. This can be explained by the load-bearing second ply being located 2.6 mm rather than 1.5 mm from the surface. This reasoning is consistent with their very similar performance in the grain direction.

The relatively lower MOR of 2.6 mm aspen plywood in the cross direction, relative to aspen made from 1.5 mm veneers, can be an acceptable result if the cross MOR is not a major concern, i.e., in unidirectional loading. The 2.6 mm veneers resulted in lower density, as well as cost savings from using thicker veneers and using less glue.

As thickness increased, MOR in the grain and cross directions gradually approached each other, as can be seen from Figure 3. The MOR in the grain direction decreased with increasing thickness and vice versa in the cross direction. This is expected because with an increasing number of layers, cross layers represent more of the mass far from the neutral axis, where MOR and stiffness are impacted. Additionally, with more layers, the number of cross layers approaches the number of layers in the grain direction. Therefore, higher numbers of layers are favourable in two-dimensional loading conditions. In unidirectional loading, such as with plywoods used for truck floors, cross layers are still needed to minimize shape deformations and for the flatness of the panel. In these plywoods, MOR in the grain (loading) direction can be increased by replacing cross layers with grain-direction veneers.

It was noticed in the bending tests that black alder showed a very brittle failure while aspen had the most ductile failure of the three species investigated. This could be due to the processing of veneers or properties of the wood species. In most engineering structures or load-bearing constructions, ductile failure is preferred. In bending tests, all black alder specimens failed suddenly without any pre-failure cracking noises. The specimen almost completely separated in brittle failure. Aspen test pieces made loud cracking noises before ultimate failure in bending, and after their peak load and load removal, the test piece recovered from some of the deformation. Much more energy was needed to completely break the aspen specimens, resulting in better toughness. Energy damping of aspen is, therefore, expected to be better than that of black alder. Figure 4 illustrates the brittle failure of the black alder and ductile failure of the aspen plywood specimen.

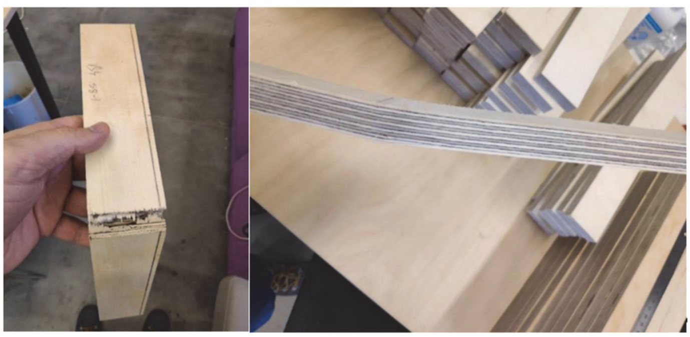

**Figure 4.** Test pieces after bending tests, showing brittle failure in black alder (**left**), and ductile failure in aspen (**right**) plywood.

In this work, parameters such as soaking temperature and peeling parameters for different species were not investigated. All three species were soaked at 40 °C. However, the peeling and roughness properties could be impacted by soaking temperature, which may impact the properties of plywoods made from these veneers. In future experiments, peeling parameters could be changed to obtain better results for lathe checks and less cracks.

## 5. Conclusions

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

- Aspen was compressed more under the 1.4 MPa pressing pressure of this study than birch or black alder, resulting in thinner, denser aspen panels. A few were below allowable thickness limits according to European standards for plywood tolerances and dimensions. Using lower pressure, a lower-density aspen plywood can be produced.
- Aspen veneers consumed the most glue, especially the 2.6 mm veneers, while black alder glue consumption was very similar to that of birch. Despite this, total glue consumption was 33%~40% lower for 2.6 mm aspen than for pure birch plywood because of the smaller number of glue lines.
- Birch plywood had the highest density, followed by 1.5 mm aspen and then black alder plywood. Aspen 2.6 mm plywood had the lowest density. Using thicker veneers in production can reduce glue consumption and result in lower density and cost.
- Birch plywood had the highest MOR in every case. Pure black alder had the lowest grain direction MOR, ~30% less than that of birch. The other five plywood types had 17%~22% less MOR than birch plywood in the grain direction. In the cross direction, birch plywood has the highest MOR and aspen with 2.6 mm thick veneers the lowest. However, the second highest stiffness came from combination plywood with birch face veneers and 2.6 mm aspen core veneers. These data quantify the impact of alternate species on plywood properties.
- For all species and combinations, grain and cross grain MOR values converged as the panels became thicker.
- MOE followed the same trends as MOR for all plywoods.
- Where the end use requires ductile materials, black alder should be avoided as it breaks with brittle failure.
- Thicker 2.6 mm aspen veneer produced plywood with lower density and lower glue consumption, and used lower priced wood than birch plywood produced from 1.5 mm veneers, but had lower MOR and MOE. Placing birch veneers at the surface made almost no difference in the grain direction MOR and MOE but significantly improved the cross-direction properties.

When considering alternative species and veneer thickness options in plywood production, it is good to keep in mind all of the aspects above as well as end use, costs, and proximity of log yard for transportation. Aspen plywood, especially using thicker veneers, would seem to be lighter and cheaper, but the MOR is lower than that of birch. This work helps in understanding the impact of species and veneer thickness substitutions on the properties of birch plywood.

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# Appendix 2

**Publication II**

Kallakas, H. Akkurt, T.; Scharf, A.; Mühls, F.; Rohumaa, A.; Kers, J. (2024). The Effect of Hardwood Veneer Densification on Plywood Density, Surface Hardness, and Screw Withdrawal Capacity. Forests, 15 (7), #1275.

forests

MDPI

Article

# The Effect of Hardwood Veneer Densification on Plywood Density, Surface Hardness, and Screw Withdrawal Capacity

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**Abstract:** Increasing environmental awareness and the carbon-storing capability of wood have amplified its relevance as a building material. The demand for high-quality wood species necessitates exploring alternative, underutilized wood sources due to limited forest areas and premium wood volume. Consequently, the veneer-based industry is considering lower-value hardwood species like grey alder (*Alnus Incania*), black alder (*Alnus glutinosa*), and aspen (*Populus tremula*) as substitutes for high-quality birch (*Betula pendula*). Initially less appealing due to their lower density and mechanical properties, these species show promise through densification, which enhances their density, strength, and hardness. This study aims to enhance plywood screw withdrawal capacity and surface hardness by densifying low-density wood species and using them in plywood face-veneer layers, or in all layers. The relationship between the wood density, surface hardness, and screw withdrawal capacity of plywood made of low-value species like aspen and black alder is examined. Experimental work with a pilot-scale veneer and plywood production line demonstrates improved surface hardness (65% and 93% for aspen and black alder, respectively) and screw withdrawal capacity (16% and 35% for aspen and black alder, respectively) in densified face veneer plywood. This research highlights the potential of densified low-value wood species to meet construction requirements, expanding their practical applications.

**Keywords:** veneer; plywood; densification; density; screws; surface hardness



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## 1. Introduction

Wood's relevance as a building material has grown due to increased environmental awareness and wood's ability to store carbon, which plants receive as carbon dioxide from the atmosphere via photosynthesis. New procedures for increasing the characteristics of wood have been developed, expanding the areas of its use and the range of conceivable applications [1]. This situation underscores the significant reliance on high-quality wood species, prompting the exploration of alternative, underutilized wood sources due to limitations in forest area and the available volume of such premium wood. Consequently, the veneer-based industry is actively seeking substitutes for high-quality birch (*Betula pendula*), considering lower-value hardwood species like grey alder (*Alnus Incania*), black alder (*Alnus glutinosa*), and aspen (*Populus tremula*). These species, characterized by lower density, hardness, and mechanical properties, were initially less appealing to the industry.

However, research suggests that wood densification presents a viable avenue for enhancing wood's performance, thus potentially promoting the utilization of these alternative, low-value wood species [2–4]. This favourable process enhances various aspects of wood, including density, strength, and hardness [5]. Particularly significant for low-density wood, densification improves its suitability for advanced engineering structures and applications [6]. Wood density, a key characteristic influenced by densification, holds considerable importance for the forest industry, impacting the suitability of wood as a raw material for wood polymer composites [7]. Densified plywood, in which wood veneers have been compressed to increase their density, has various practical applications across different fields. Research has shown that densified plywood offers advantages such as shorter pressing times, reduced glue consumption, and lower pressing pressures without compromising bonding strength [8].

Densified plywood, which undergoes a process to enhance its structural properties, finds several practical applications. In construction, densified plywood serves as an inexpensive alternative to solid wood boards. It can be used for floors, walls, and roofs due to its strength, durability, and resistance to warping and cracking [5]. In the automotive industry, densified plywood can be used in car interiors, such as dashboards and door panels. In marine applications, its improved dimensional stability and resistance to bio-deterioration make it useful for boat interiors and decks.

Screws have become increasingly common in plywood applications when it is used as a construction material. However, low-density wood species do not have enough screw withdrawal capacity when used in construction or packaging. The screw withdrawal resistance in plywood is influenced by various factors such as wood species, surface hardness, density, and shear strength. The withdrawal capacity of screws is affected by the wood species. Ayteking et al. [9] showed that high-density wood species such as oak wood exhibited the highest screw withdrawal resistance, followed by Stone pine (*Pinus pinea*), black pine (*Pinus thunbergia*), and fir (*Abies*). The withdrawal capacity of wood screws is positively correlated with wood density, as evidenced by a study on Japanese larch cross-laminated timber, which demonstrated that with a density increment of 0.05 $g{\cdot}cm^{-3}$, the withdrawal capacity increased by an average of 9.4% [10]. Similarly, it has been reported that there is a positive linear relationship between the withdrawal capacity of the screw and the specific gravity [11]. The relationship between residual density and screw withdrawal capacity has been found to be directly proportional, indicating that screw withdrawal capacity decreases as wood density decreases through biodegradation [12].

Furthermore, the shear strength of wood is a crucial factor in assessing screw withdrawal load resistance, as it describes the connection between wood fibres and the screw [13]. Mclain's [14] work suggests that smaller-diameter fasteners in low-density species may require a change in design strength. The established relationship between wood density and screw withdrawal capacity suggests that a lower density corresponds to a decreased screw withdrawal capacity, while a higher density correlates with increased capacity [12,15]. These findings underscore the pivotal role of wood density in determining fastener withdrawal capacity. Consequently, research aims to densify low-density wood species to enhance their screw withdrawal capacity.

In veneer-based products, it is possible to densify each veneer layer separately and combine them in composites in such way that you can only have outer layers densified to achieve optimal strength. In this case, the surface hardness will be important factor that is shown to significantly increase with the densification process [16]. Furthermore, the radial densification of wood has been shown to enhance its hardness across three anatomical directions [17], while surface densification has demonstrated significant improvements in the Janka hardness of wood, particularly at higher pressing temperatures [18]. This process also holds promise for enhancing the hardness of the outer layers of veneer-based products, thereby opening new avenues for the utilization of low-density species [19], which in turn contributes to increased screw withdrawal capacity [20].

In addition, in hybrid cross-laminated timber, the withdrawal resistance of screws is influenced by the contact area between the screw and the wood material, revealing a link between withdrawal resistance and hardness [21]. This relationship extends to various panel materials, where the screw withdrawal capacity increases with higher panel density and cellulose nanofibril (CNF) addition ratio, indicating a correlation between hardness and screw withdrawal capacity [15]. Notably, improvements in wood's strength properties resulting from densification have been shown to enhance the holding capacity of fasteners [22]. Moreover, research underscores the significant impact of wood densification on the withdrawal capacity of nails (up to 200%) and screws (up to 140%) [23].

This study examined the need to support or disapprove the claim that using densified low-value wood for plywood face veneers will increase the fastener holding capacity, making it enough for construction applications. For this, low-value and low-density wood species such as aspen and black alder were densified and used in plywood face veneers or in all layers. This research tested the hypothesis that adding only densified face veneers to the plywood will increase the fastener holding capacity of the whole plywood panel, and with harder surfaces will produce a higher screw holding capacity. The relationships between the surface hardness and screw withdrawal capacity of plywood made of different low-value hardwood species with and without densification were examined.

## 2. Materials and Methods

### 2.1. Veneer Preparation

This study used veneers from three distinct hardwood species for plywood production: silver birch (*Betula pendula* Roth), black alder (*Alnus glutinosa* L.), and common aspen (*Populus tremula* L.). Aspen and alder were selected as low-value and underutilized wood species in Estonia, offering alternatives to extensively used birch in the North European plywood industry. These hardwood species, despite having lower density and strength, have previously been established as suitable for alternative species to birch in plywood [24,25]. The logs were freshly felled in October 2022 at Järvselja, Tartu County, Estonia, Järvselja Learning and Experimental Forest Foundation. The birch trees had an average stand age of 59 years, the black alder 26 years, and the aspen 66 years, all weighted by area. The log nominal lengths were 3 m, and average diameters were 24 cm (birch), 26 cm (black alder), and 33 cm (aspen).

The rotary-peeling method was based on our previous study; Kallakas et al. [25]. The logs were cut into 1.3 m long peeler blocks and immersed in a water bath at 40 °C for 24 h. Before peeling, peeler blocks were debarked and variables such as temperature, moisture content (MC), log length, and annual ring widths were measured. After that, peeler blocks were rotary-peeled into 3.34 mm-thick green veneer using an industrial-sized peeling lathe (Model 3HV66; Raute Oyj, Lahti, Finland). Peeling speed was 60 m·min$^{-1}$, knife sharpening angle 19°, and compression rate 7%. After the peeling process, the veneer matt was cut into sheets with dimensions of 900 × 450 mm$^2$ using a pneumatic guillotine (Wärtsilä Corporation, Helsinki, Finland). Subsequently, veneer sheets were dried in a laboratory-scale veneer dryer (Raute Oyj, Lahti, Finland) at 170 °C. The drying cycle durations varied based on wood species and veneer thickness, as outlined in Table 1. After, veneers were stored at 25 ± 2 °C and 20 ± 5% relative humidity (RH) in the conditioned room to maintain a target moisture content of 4.5 ± 1.5%, which is necessary for subsequent gluing applications.

**Table 1.** Drying times of different hardwood veneer thicknesses.

| | Veneer Thickness (mm) | |
|---|---|---|
| **Wood Species** | **1.5** | **3.0** |
| Birch | 150 s | |
| Black alder | 160 s | 390 s |
| Aspen | 170 s | 420 s |

### 2.2. Veneer Densification

Following conditioning and drying, veneers free of any wood flaws were picked out with care and then cut into 280 × 430 mm$^2$ pieces. After that, the specimens were densified with a thermo-mechanical process at Luleå University of Technology, located in Northern Sweden. Densified veneer samples with dimensions of 50 × 200 $mm^2$ were produced. The specimens were conditioned at 20 ± 2 °C and 65 ± 5% RH until they reached equilibrium moisture content (EMC) prior to densification. Densification was carried out at relatively low temperatures by purposefully allowing an increase in MC to lower the glass-transition temperature [26]. In a laboratory hot press (HLOP15, Höfer Presstechnik GmbH, Taiskirchen, Germany), the veneers were compressed uniaxially between heated plates (150 °C). Here, 1.5 mm was set as the target veneer thickness, which was upheld by mechanical stops. The target compression ratio was achieved by starting with an initial thicknesses of 3.0 mm and compressing down to 50%. After placing the specimens on the heated plate, the pressing cycle was started.

A specimen lost about 1% of its MC between the start of the cycle and complete contact with both press hotplates. To plasticize the wood, a low contact pressure was first applied and maintained for 10 s to raise the surface temperature. After that, the pressure was raised to achieve a compression rate of 0.1 $m \cdot s^{-1}$ until the desired thickness was attained. The specimens were kept hot and under pressure for 240 s. Afterward, the press's interior water circulation was used to cool the platens until they reached 35 °C (6 min). The pressure was removed once the cooling procedure was complete. Before undergoing any processing, each specimen was thereafter securely wrapped in plastic film to avoid moisture changes.

### *2.3. Plywood Manufacturing*

The plywood lay-up schemes were developed using the standard cross-band construction approach, resulting in three plywood types with seven layers, as detailed in Table 2 and Figure 1. Plywood specimens were prepared with dimensions of 200 × 50 × 9 mm. Undensified plywood served as the control (UN), made with undensified 1.5 mm thick veneers. FVD and AVD plywoods were made of 3.0 mm densified face veneers or with all layers of densified veneers, respectively. For plywood making, phenol formaldehyde (PF) resin (Prefere Resins Finland Oy, Hamina, Finland) with a solid content of 49% was used. Using an adhesive roller (Black Bros 22-D, Mendota, IL, USA), glue was applied to each glue line while the spread rate varied depending on wood species due to the different surface roughness. Total glue consumption was calculated by weighing the veneers before and after spreading (Table 3).

**Table 2.** Plywood type description.

| Plywood Type | Abbreviation | Lay-Up |
|---|---|---|
| Undensified | UN | $N^{1.5}$-$N^{1.5}$-$N^{1.5}$-$N^{1.5}$-$N^{1.5}$-$N^{1.5}$-$N^{1.5}$ |
| Face veneer densified | FVD | $D^{3.0\to1.5}$-$N^{1.5}$-$N^{1.5}$-$N^{1.5}$-$N^{1.5}$-$N^{1.5}$-$D^{3.0\to1.5}$ |
| All veneers densified | AVD | $D^{3.0\to1.5}$-$D^{3.0\to1.5}$-$D^{3.0\to1.5}$-$D^{3.0\to1.5}$-$D^{3.0\to1.5}$-$D^{3.0\to1.5}$-$D^{3.0\to1.5}$ |

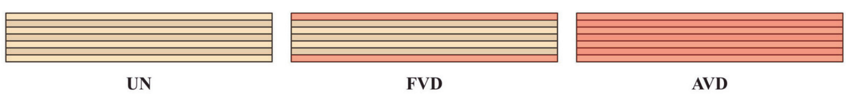


**Figure 1.** Plywood lay-up schemes (yellow—undensified veneers, orange—densified veneers).

The panels were then subjected to hot pressing using a hydraulic press at 130 °C with a pressing pressure of 1.4 MPa. For the study, a total of 90 plywood samples were constructed. To assess the effect of densification, aspen and black alder veneers that were initially 3.0 mm thick were densified to 1.5 mm. The purpose of this stage was to study how the densification of veneers will affect various plywood properties. After, specimens were cut into the respective dimensions for further testing and conditioned at in an environment with a 65 ± 5% RH and a temperature of 20 ± 2 °C.

**Table 3.** Glue consumptions of different plywood types.

| Wood Species | Plywood Type | Glue Consumption g·m$^{-2}$ |
|---|---|---|
| Birch | UN | 160 (±10.6) |
| | UN | 173 (±7.5) |
| Black alder | FVD | 160 (±7.2) |
| | AVD | 133 (±2.2) |
| | UN | 165 (±10.9) |
| Aspen | FVD | 159 (±19.3) |
| | AVD | 136 (±7.2) |

### *2.4. Density Determination*

The density of densified and undensified plywood samples was determined in accordance with EN 323 [27]. A sliding calliper was used to measure length, width, and thickness to an accuracy of 0.01 mm. The test specimens were weighed on a balance with an accuracy of 0.001 g. The test specimens were cut into squares with nominal side lengths of 50 mm. Overall, 90 samples were evaluated. Test specimens with constant mass were conditioned in an environment with a 65 ± 5% RH and a temperature of 20 ± 2 °C. The density of plywood samples was calculated by dividing the weight of the specimens by volume.

### *2.5. Brinell Hardness Determination*

The Brinell hardness values of the densified and undensified plywood samples were determined using the procedures outlined in the EN 1534 [28]. Prior to testing, specimens were conditioned in an environment with a 65 ± 5% RH and a temperature of 20 ± 2 °C. Then, the specimen's surface was indented with a 10 mm diameter hardened steel ball under a 1000 N load for 25 s using the universal electromechanical testing machine (Zwick/Roell Z050, ZwickRoell GmbH, Ulm, Germany). The diameter of the indentation left in the specimen was measured using a calliper with an accuracy of 0.01 mm. The Brinell hardness number was obtained by dividing the applied load by the area of the indentation. Overall, 90 samples were evaluated.

### *2.6. Screw Withdrawal Capacity and Load Determination*

All tests for the screw withdrawal capacity and load determination were conducted on the universal electromechanical testing machine (Zwick/Roell Z050, ZwickRoell GmbH, Germany) according to EN 13446 [29]. Prior to testing, specimens were conditioned in an environment with a 65 ± 5% RH and a temperature of 20 ± 2 °C until constant mass was achieved. Screw withdrawal capacity test was performed from the tangential section of densified and undensified plywood surfaces. A crosshead loading rate of 2 mm·min$^{-1}$ was applied until maximum load was achieved. Ultimate withdrawal load was determined, and screw withdrawal capacity was calculated, dividing the ultimate load by the radius and penetration depth of the screw. For that, 3.0 × 50 mm galvanized wood screws were used in this test and, overall, 90 samples were evaluated.

### *2.7. Statistical Analysis*

For statistical analysis, a one-way ANOVA was performed on all groups with an alpha level of 0.05. When a significant *p*-value was observed, the Bonferroni correction was applied by adjusting the alpha level for multiple comparisons (*t*-tests). The new alpha level was set at 0.017 for three comparisons. The Pearson correlation coefficients ($r$) and corresponding *p*-values were computed using MS Excel's Data Analysis Toolpak/Regression to assess the strength and direction of the relationships between variables, such as density and Brinell hardness and screw withdrawal capacity.

## 3. Results and Discussion

### *3.1. Density of Plywood*

To see how wood densification will affect low-value hardwood species-based plywood densities and how they compare to those of standard birch plywood, samples with all layers densified (AVD) and only face veneers densified (FVD) were made and compared with undensified (UN) samples. The densities of plywood samples made from different hardwood species and densified veneer layers are shown in Figure 2. From these results, it can be seen that the density of plywood is significantly ($p < 0.017$) influenced by the hardwood species used. Veneer densification clearly increases the density of aspen and black alder plywood. As expected, the highest density was achieved when all layers of plywood were densified. Black alder FVD and AVD plywood stood out by achieving a density similar to or higher than the 824.30 kg·m$^{-3}$ density of UN birch plywood (821.98 kg·m$^{-3}$ and 896.73 kg·m$^{-3}$, respectively). Furthermore, black alder AVD plywood showed a density 72.43 kg·m$^{-3}$ higher ($p = 0.005$) than the density of birch UN plywood.

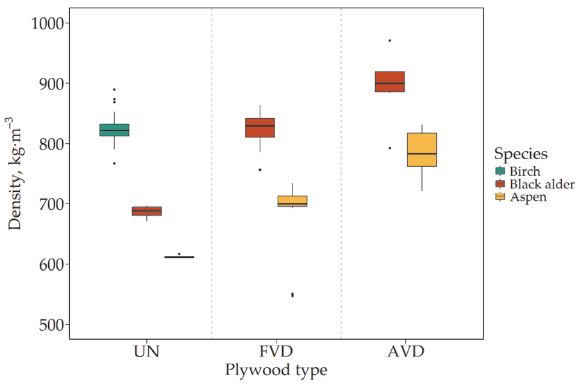


**Figure 2.** Average density values for the tested plywood types.

Within aspen and black alder plywood samples, all the different plywood types showed significant differences in densities ($p < 0.017$), proving that densification greatly influenced the density of the plywood. This is understandable when considering that a higher number of densified veneers in plywood will also increase the overall plywood panel density. Similarly, Bekhta et al. [30] showed that wood species and different types of veneer densification have great effects on plywood density. Madhoushi et al. [23] showed that a 50% densification level will increase the plywood density by nearly two times. In our instance, we had a 50% densification ratio of black alder and aspen veneers. These densified veneers were added to the plywood lay-up as face veneers (FVD) or in all layers (AVD). In the instance of black alder, we observed a 20% and 31% increase in density for FVD and AVD plywood, respectively, as compared to UN plywood while with aspen, similarly, we saw a 11% and 28% increase in density for FVD and AVD plywood, respectively, as compared to UN plywood.

The density of plywood is also influenced by the glue consumption [2,24]. In our study, we saw a deviation in glue spreading rates (Table 3), where AVD plywood had lower glue consumption due to compressed structure and smoother surfaces (not measured in this study). However, the density of these plywood types (AVD) was still the highest, emphasizing how significantly the final plywood density is affected by the addition of densified veneers into the plywood.

### *3.2. Brinell Hardness of Plywood*

As demonstrated above, compressing the veneers increases the overall density of the plywood. Here, we see that veneer densification will also lead to a significant ($p < 0.017$)

increase in Brinell hardness compared to UN plywood (see Figure 3). The Brinell hardness of the FVD aspen and black alder plywood was 65% and 93% higher, respectively, compared to the UN plywood. This significant change in hardness due to densification has previously been found in several research studies and could be attributed to the closing of the vessel and fibre lumens as well as lathe check conglutination [31–34]. However, we saw no significant ($p > 0.5$) increase compared to FVD plywood in the Brinell hardness when all layers of plywood lay-up were densified (AVD). This could be explained with the Brinell hardness measurement method, where hardness is only obtained from the one surface of the plywood panel, and other layers did not have an effect on the hardness of the plywood. However, previous studies have highlighted that hardness values are greatly dependant on the wood density and force applied to wood composites, and the deeper the indenter penetrates, the more the values are influenced by the undensified wood's hardness [35–39].

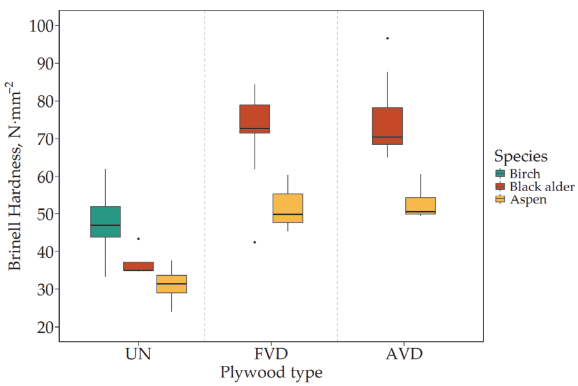


**Figure 3.** Average hardness values for the tested plywood types.

Furthermore, it is shown that Brinell hardness can benefit from more layers of densified wood in the composite [40]. In our study, the data indicated that the substrate had no effect on the surface hardness of the plywood. We measured the Brinell hardness with a constant applied force of 1000 N and the results of the hardness tests were largely governed by the face veneer density rather than the entire plywood layup. This may be attributed to the combination of the force applied to measure hardness and the high density of the substrate, which was sufficient to withstand the indentation force. Alternatively, it could be due to the sufficient deformation of the densified layer itself, which deformed enough to prevent the substrate from influencing the hardness values.

When comparing the densification effect of low-value wood species to the hardness of birch control UN plywood samples, it is evident that densification significantly increases the surface hardness of low-value wood, matching or even surpassing that of birch (Figure 3). Aspen FVD plywood had a similar surface hardness to birch ($p = 0.041$), while AVD samples showed a slightly higher surface hardness than birch ($p = 0.013$). At the same time, black alder FVD and AVD plywood samples had significantly ($p < 0.017$) higher surface hardness than UN birch plywood.

The hardness data revealed that both species saw an increase in Brinell hardness from control specimens for both densified plywood types, with only a little difference between them (FVD and AVD, respectively). Increasing the surface hardness through densification broadens the variety of uses for low-value species, particularly in furniture applications, where the material is exposed to the user, as well as in flooring applications.

### 3.3. Screw Withdrawal Load and Capacity of Plywood

We looked for the densification effect on low-value hardwood plywood screw holding properties. A positive trend in veneer densification was clearly visible on both screw withdrawal load and capacity (Figure 4). Here, we see that in the case of black alder (AVD plywood type), the veneer densification led to highest screw withdrawal load (1997.79 N) and capacity (59.38 N·mm$^{-2}$). However, it was still not significantly higher ($p$ = 0.022) than the birch UN plywood screw withdrawal capacity (57.87 N·mm$^{-2}$).

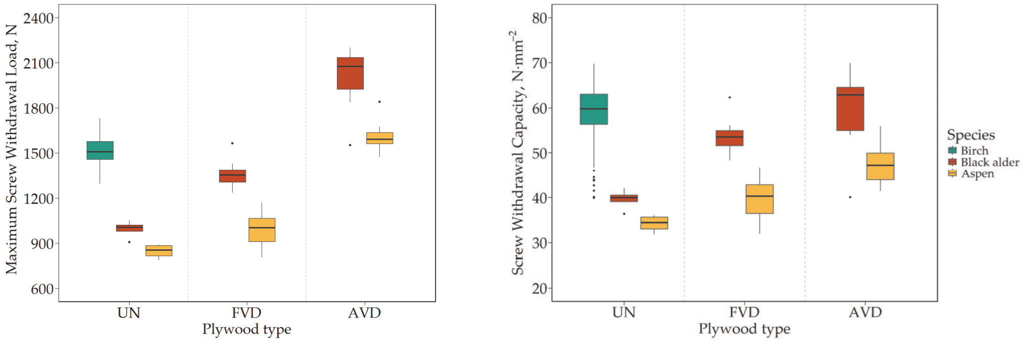


**Figure 4.** Average screw withdrawal load (**left**) and capacity (**right**) values for the tested plywood types.

Another notable observation is that the incorporation of additional densified layers into black alder plywood lay-up did not substantially enhance the screw withdrawal capacity, showing an increase of only 5.74 N·mm$^{-2}$ (comparing FVD to AVD plywood), which was not statistically significant ($p$ = 0.140). That is not the case with the maximum screw withdrawal load, where the AVD clearly shows a significantly ($p$ < 0.017) higher maximum withdrawal load than the FVD plywood. That is reasonable because of the set recovery effect in densified plywood samples, where AVD plywood thickness becomes higher than the FVD plywood thickness, when densified veneers expand over time. Due to that, screw withdrawal capacity, which is calculated from load divided by thickness, reduces its significance. Conversely, when considering only the load (excluding thickness), there remains a highly significant difference between the FVD and AVD plywood types.

Aspen fibres are generally loose in wood products, which leads to a low fastener holding strength. Here, we looked to improve the aspen screw holding capacity through veneer densification, which leads to a more compact structure of the wood. When looking at the veneer densification effect on aspen plywood types, then we can see a significant ($p$ < 0.017) increase in both screw withdrawal load and capacity for all the plywood types as compared to the UN plywood. This improvement could be attributed to the compressed fibres and compact structure of densified wood, which leads to a better connection between screw threads and wood that increases with a higher number of densified layers in the plywood lay-up. However, none of the densified aspen plywood variants achieved the screw withdrawal capacity of birch UN plywood.

Based on our data, we can say that we are able to greatly improve the screw holding capacity (35% and 16% for FVD black alder and aspen, respectively) by just adding a face layer of densified wood to plywood (when compared to UN plywood). Higher improvements were achieved when all layers of plywood were densified (50% and 38% for AVD black alder and aspen, respectively) as compared to UN plywood. In construction applications such as floors, walls, and roofs, this increased screw withdrawal load and capacity enables the use of low-value wood species in densified plywood lay-up. Furthermore, this increased screw withdrawal capacity broadens the use of low-value hardwood plywood for furniture connections and as a packaging material.

### *3.4. Density-Specific Mechanical Properties*

In this study, we examined plywood samples with varying densities (UN, FVD, AVD). To see if there were any correlations and to understand the effect of density on the surface hardness of the plywood, the density values were plotted against the Brinell hardness

(Figure 5). The most notable observation was that the highest density plywood (AVD) did not result in a significant increase in surface hardness compared to the FVD plywood. As said before, this could be elucidated using the Brinell hardness measurement method, which derives hardness solely from one surface of the plywood panel and is less affected by the other layers within the plywood.

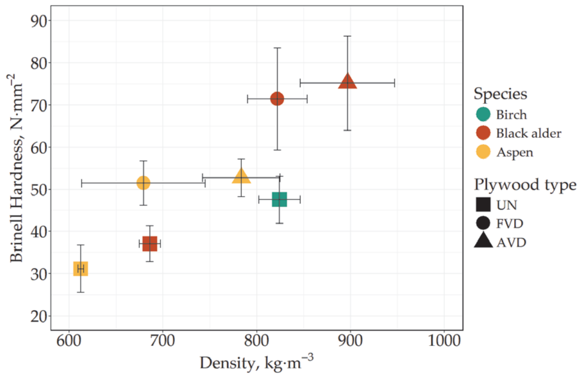


**Figure 5.** Plywood density vs. surface hardness.

Next, this research looked at how well the density of plywood can correlate to surface hardness. The data for all the plywood samples combined gives a positive correlation of $r = 0.50$ and $p < 0.05$, suggesting that plywood density has an impact on surface hardness. When looking at the different plywood types, then we can see that adding one layer of densified veneer (FVD plywood type) will have positive correlation ($r = 0.54$ and $p < 0.05$ for aspen plywood and $r = 0.92$ and $p < 0.05$ for black alder plywood) with density and surface hardness as compared to UN plywood. With AVD plywood types, the significant positive correlations compared to UN plywood stay the same.

However, when adding more layers of densified veneers into the plywood lay-up, thereby increasing the overall density of the plywood, the surface hardness increase is not significant. In this case, we see only slight positive correlations between density and surface hardness, which are not significant ($r = 0.36$ and $p = 0.13$ for FVD vs. AVD aspen plywood and $r = 0.38$ and $p = 0.12$ for FVD vs. AVD black alder plywood). This suggests that surface hardness is only significant influenced by the top layer density of the plywood. However, surface hardness could also be influenced by the force exerted on the wood composite; as the indenter penetrates deeper, the values could be increasingly influenced by the hardness of the undensified wood [35–37]. In this study, we kept force constant (1000 N) and did not observe this effect.

We saw previously that the screw withdrawal capacity was positively correlated with plywood type (Figure 4, right). Therefore, we looked at how well it correlates with plywood density. As expected, the screw withdrawal capacity was heavily influenced by the plywood density (Figure 6) and all our plywood types had a statistically significant strong positive correlation between plywood density and screw withdrawal capacity ($r = 0.776$ and $p < 0.05$). These strong positive correlations stayed the same between all the plywood types within the wood species. This is consistent with the general tendency for wood materials to have a higher screw withdrawal capacity when wood density is higher [41–44]. It also supports our hypothesis, that increasing the low-value wood density by densification will lead to higher screw holding capacity. However, when looking at density increase versus screw withdrawal capacity in comparison with birch UN plywood, then only black alder manages to reach a similar screw withdrawal capacity. While the density of the black alder AVD plywood is 9% higher than birch UN plywood ($p = 0.005$), the screw withdrawal capacity difference is not significant ($p = 0.681$).

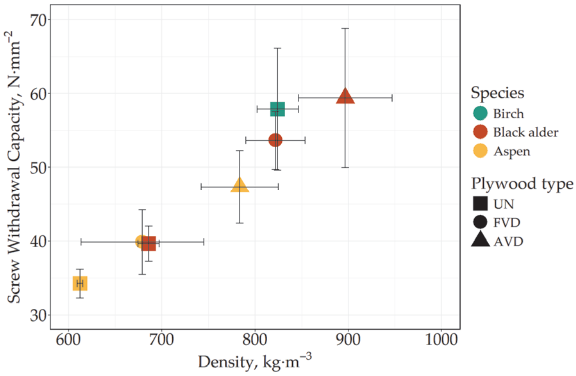


**Figure 6.** Plywood density vs. screw withdrawal capacity.

Because surface hardness is one of the main properties that is greatly influenced by wood densification, as seen above (Figure 3), it is also important to consider how well surface hardness contributes to screw withdrawal capacity. The positive effect of increasing the surface hardness on the screw withdrawal capacity is visible in Figure 7. After adding one layer of densified aspen veneer with a higher surface hardness to the aspen plywood, the screw withdrawal capacity is increased by 16% (comparing aspen UN plywood to aspen FVD plywood type) which gives a positive correlation of $r = 0.495$ between surface hardness and screw withdrawal capacity, although this is not significant ($p = 0.061$). The correlation is improved when all layers are densified (comparing aspen UN plywood to aspen AVD plywood type), giving a significant positive correlation of $r = 0.568$ and $p = 0.004$.

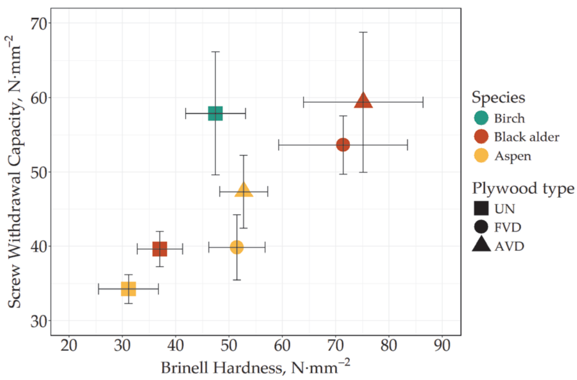


**Figure 7.** Plywood surface hardness vs. screw withdrawal capacity.

However, with black alder, we see a much higher (35%) screw withdrawal capacity increase with the surface hardness increase from black alder UN plywood to black alder FVD plywood, giving a significant strong positive correlation between surface hardness and screw withdrawal capacity ($r = 0.863$ and $p < 0.05$). Conversely, we saw only slight positive correlations which were not significant ($r = 0.330$, $p = 0.167$ and $r = 0.316$, $p = 0.200$ for aspen and black alder plywood, respectively) between surface hardness and screw withdrawal capacity when adding more layers of densified veneers to plywood lay-up (from FVD plywood to AVD plywood type). Despite surface hardness not improving significantly from FVD plywood to AVD plywood, the screw withdrawal capacity still increased by 19% ($p = 0.004$) for aspen plywood and by 11% ($p = 0.140$) for black alder plywood, although this fell short of our set threshold for statistical significance, 0.05.

This suggests that screw withdrawal capacity is affected more on the compact and dense wood structure, rather than wood surface hardness. Though we observed positive correlations between the UN and FVD plywoods' surface hardness and screw withdrawal capacity, it can be seen that density has a major role in determining screw withdrawal capacity. Our data imply that densifying and increasing low-value wood's density might be the route to an improved screw withdrawal capacity of the plywood. This is consistent with the use of higher density wood to obtain a higher fastener holding capacity [41–44].

## 4. Conclusions

This study examined the correlations between the wood density, surface hardness, and screw withdrawal capacity of densified low-value hardwood veneer-based plywood. The aim was to understand how much difference there is if only densified face veneers were added to plywood versus incorporating all layers with densified veneers in plywood. Based on this study, the following observations can be made:

- Densifying low-value wood veneers and incorporating them into the plywood lay-up significantly increases the overall density of the plywood. However, only black alder AVD plywood gained higher density than birch UN plywood.
- A statistically significant positive correlation (r = 0.776 and $p < 0.05$) between plywood density and screw withdrawal capacity was noted, which stayed the same with all the plywood types within the different wood species. These data support the hypothesis that increased plywood density with only surface veneers densified will lead to significant screw withdrawal capacity improvement. Nonetheless, the screw withdrawal capacity of birch UN plywood remained highest, together with black alder AVD plywood.
- Having more densified layers in plywood significantly contributed to the screw withdrawal capacity. This improvement can be attributed to the compressed fibres and compact structure of the densified wood, which enhance the connection between the screw threads and the wood.
- The surface hardness of the plywood was significantly influenced by the plywood face veneer layer density. The densities of the remaining plywood veneer layers did not show any significant contribution to the surface hardness.

Overall, it was noted that adding just densified face veneers to low-value hardwood plywood lay-up will have a substantial effect on plywood density, strength, and hardness. Therefore, incorporating all densified layers into plywood lay-up is not relevant unless special properties are needed.

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# Appendix 3

**Publication III**

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# 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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A R T I C L E I N F O

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A B S T R A C T

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 suppress 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/m$^3$), black alder (*Alnus glutinosa* L.) (av. 440 kg/m$^3$), and common aspen (*Populus tremula* L.) (av. 420 kg/m$^3$). 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 Käru, 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 $\times$450 mm$^2$ (Length x 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 $\times$430 mm$^2$ (LxT). 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 $\times$200 mm$^2$ 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 $\pm$ 2 °C and 65 $\pm$ 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 µm. Measurements were conducted with step intervals of 4 µm in the radial direction, and the specimens measured 50 ×30 $mm^2$. For each sheet, DPs were collected for one non-densified and four densified specimens.

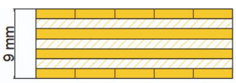
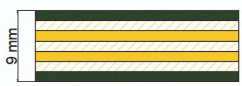
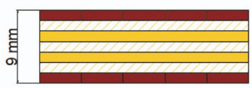
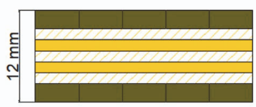
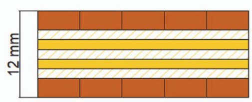
Surface roughness of the tight side of the veneer was determined before and after densification on 4 specimens per veneer sheet using light microscopy with a digital microscope (DSX1000, Olympus Corporation, Tokyo, Japan). The surface roughness was calculated from the height map of the collected image of the bark-side surface for an area of interest measuring 50 ×30 $mm^2$. The roughness was expressed as the 3D roughness parameter root mean square height (Sq), maximum height (Sv), and arithmetical mean height (Sa).

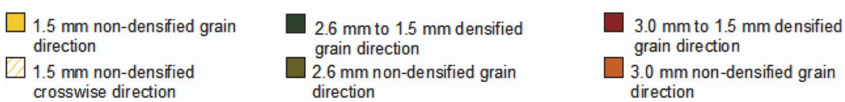
Tension test samples were conditioned at 65 % RH and 20 °C. Subsequently, tension strength parallel to the grain was tested in accordance with DIN EN 789:2004, utilizing an MTS Criterion Series 40 universal testing machine (MTS System Corporation, Eden Prairie, MN, USA) equipped with a 10 kN load cell. The tension rate employed was 0.02 mm/s, and the dog bone-shaped specimens measured 30 ×100 $mm^2$. 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 mm×300 mm. The middle layers in these samples were composed of a single piece measuring 200 mm×300 mm x 1.5 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 |  | $D^{2.6\rightarrow1.5}-N^{1.5}-N^{1.5}-N^{1.5}-N^{1.5}-N^{1.5}-D^{2.6\rightarrow1.5}$ |
| III |  | $D^{3.0\rightarrow1.5}-N^{1.5}-N^{1.5}-N^{1.5}-N^{1.5}-N^{1.5}-D^{3.0\rightarrow1.5}$ |
| IV |  | $N^{2.6}-N^{1.5}-N^{1.5}-N^{1.5}-N^{1.5}-N^{1.5}-N^{2.6}$ |
| V |  | $N^{3.0}-N^{1.5}-N^{1.5}-N^{1.5}-N^{1.5}-N^{1.5}-N^{3.0}$ |




*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 (Prefere 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/m$^2$. 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/m$^2$. In contrast, the highest glue consumption was found in 12 mm aspen plywood, where all layers consisted of non-densified veneers, averaging 187 g/m$^2$. 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/m$^3$, while the highest density was recorded in black alder type III plywood samples, reaching 846 kg/m$^3$. 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 Fmax = 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

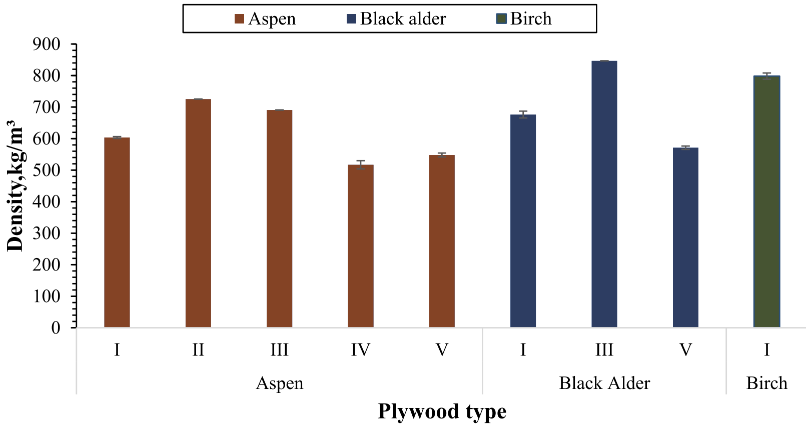



**Fig. 1.** Densities of plywood from different wood species.

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

| | Before densification | | | | After densification | | | |
|---|---|---|---|---|---|---|---|---|
| **Group** | **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.

| | Before densification | | | | After densification | | | |
|---|---|---|---|---|---|---|---|---|
| **Group** | **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

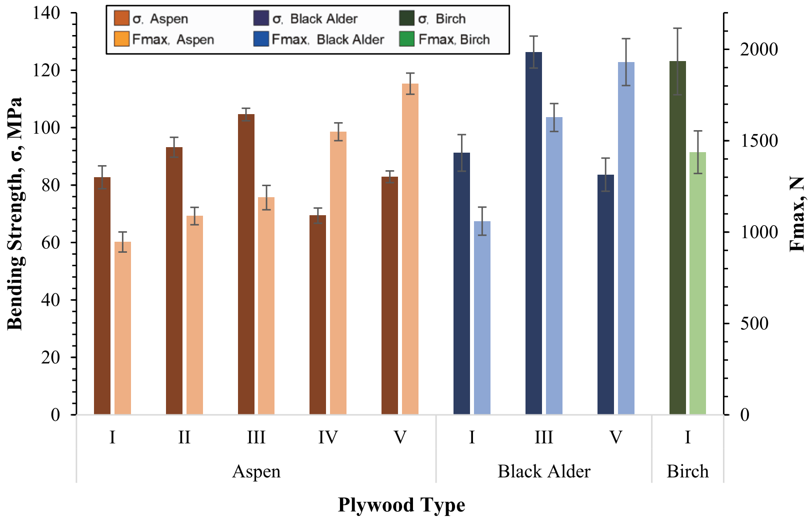



**Fig. 2.** Bending strength results compared to maximum force carrying capacity (in MPa) for 7-layer plywood.

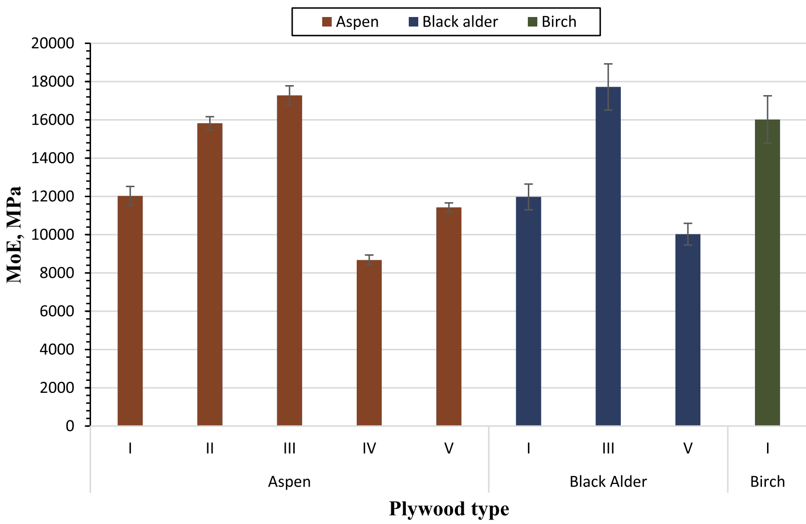



**Fig. 3.** Modulus of elasticity results (in MPa) for 7-layer plywood.

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 at 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:

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

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:

$$Bending\ strength(\sigma) = \frac{3 \quad xforcexlength}{2 \quad xwidthx \quad thickness^2} \quad (2)$$

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

$$Force = \frac{2 \quad xbending\ strengthxwidthx \quad thickness^2}{3 \quad xlength} \quad (3)$$

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 ×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):

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

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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# Appendix 4

**Publication IV**

Akkurt, T.; Rohumaa, A.; Kers, J. (2025). Effective Wood Veneer Densification by Optimizing Key Parameters: Temperature, Equilibrium Moisture Content, and Pressure. Forests, 16 (6), 969.

*forests*

*Article*

# Effective Wood Veneer Densification by Optimizing Key Parameters: Temperature, Equilibrium Moisture Content, and Pressure

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**Abstract:** Due to increasing environmental concerns and the scarcity of high-quality hardwood resources, enhancing wood properties—such as strength, surface smoothness, and impact resistance—has become essential, especially for veneer-based products. Wood densification is a promising method for such improvements, typically involving mechanical, thermo-mechanical, or hygrothermal-mechanical processes. However, most prior studies examined only one densification parameter at a time. This study systematically investigates the combined effects of equilibrium moisture content (EMC), pressing temperature, and pressure on birch veneer densification. Birch veneers were densified radially using four temperatures (90–210 °C), three pressures (1.8–5.4 MPa), and three EMC levels (5%–20%) for a fixed pressing time of 8 min, resulting in 36 unique combinations. Results showed that higher pressing pressure and higher initial EMC consistently led to greater veneer densification. Optimal outcomes were achieved under two distinct conditions: (1) 90 °C with high EMC and high pressure, and (2) 210 °C with the same high EMC and high pressure. Intermediate temperatures (130–170 °C) were less effective. Temperatures above 200 °C were found critical due to lignin softening beyond its glass transition temperature. These findings highlight the interactive role of key parameters and provide practical guidance for upgrading low-quality veneers into high-performance engineered wood products in a sustainable and resource-efficient manner.

**Keywords:** birch; density; veneer densification; hygro-thermal; set-recovery

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## 1. Introduction

With the growing global demand for sustainable construction materials and increasing pressure on forest resources, improving the properties of wood has become essential. Natural wood often exhibits limitations such as low strength, dimensional instability, and surface irregularities, especially in fast-growing or low-density species. Enhancing these properties is crucial for expanding the usability of underutilized species and improving the performance of high-grade woods. By compressing the cellular structure of wood under heat and pressure, densification significantly increases density, strength, surface hardness, and dimensional stability of wood, making it a viable alternative to tropical hardwoods and synthetic materials.

Wood densification is a widely studied technique aimed at improving the physical and mechanical properties of low-density wood species, making them viable alternatives to traditional high-density species in structural and decorative applications [1–3]. The efficiency and quality of densification, however, are strongly dependent on several factors, including temperature, pressing pressure, and the wood's initial equilibrium moisture content (EMC) [3–5].

One of the key mechanisms in the densification process is the softening of the wood cell wall components—primarily lignin and hemicellulose—when subjected to heat. Lignin, in particular, exhibits a glass transition temperature that varies depending on moisture content, becoming thermo-plastically active and allowing for permanent deformation of the wood structure [5]. At elevated temperatures, such as those above 200 °C, this thermal softening dominates the deformation behavior, often compensating for reduced plasticization by moisture. Through the application of heat (typically between 150 °C and 170 °C), pressure, and steam, wood can be compacted to significantly improve its density and strength [6]. Also, several studies have confirmed that higher pressing temperatures during densification improved compressibility and stability. For instance, Bekhta and Niemz [7] found that heating spruce wood at 200 °C in densification improved dimensional stability, although they noted reductions in bending strength and modulus of elasticity (MoE) at excessive temperatures. Similarly, Fang et al. [3] reported improved dimensional stability in the 180–220 °C densification temperature range, with no set recovery observed at 220 °C.

Alongside temperature, pressing pressure significantly affects densification outcomes. Higher pressures promote greater cell wall collapse and compaction, leading to higher final densities and improved mechanical performance. For example, Huang W. [8] applied pressures up to 20 MPa to basswood blocks and observed tensile strength increasing from 5 to 10 MPa, followed by a decrease beyond 10 MPa. Bekhta et al. [9] found that increasing pressing pressure from 4 to 12 MPa reduced surface roughness. Navi and Girardet [10] demonstrated that densification under high pressures significantly improved the shear strength and Brinell hardness of spruce, pine, and beech samples.

Studies by Kutnar et al. [11] and Rautkari et al. [12] emphasized the importance of high initial EMC or steam-assisted densification in improving compressibility and structural stability.

Scharf et al. [13] investigated the hardness of surface-densified wood and emphasized that density profiles and test parameters significantly influence hardness results, highlighting the need for standardized testing methods or profile-based evaluation.

In our earlier research, it was found that densification of face veneers significantly improved the bending strength, load-carrying capacity, screw withdrawal resistance, surface hardness, and material efficiency of aspen and black alder plywood [14,15]. However, there remains a need to define optimal wood densification process conditions based on a systematic evaluation of densification parameters. Most of the research has focused on densification at higher temperatures and on solid softwood, which results in a less homogeneous final outcome due to variations in compression properties across grain directions, and differences in the densities of earlywood and latewood. The aim of this study is to gain insight into the combined effects of densification process parameters through optimization using lower pressures, lower temperatures, and shorter densification cycle durations.

This study investigates the effects of temperature, pressure, and EMC on the densification behavior of hardwood veneers, with a focus on density changes, compression ratios, and set recovery. By systematically analyzing these parameters across a range of processing conditions, we aim to identify optimal densification regimes suitable for industrial-scale production, promoting enhanced dimensional stability and reduced energy consumption.

## 2. Materials and Methods

### 2.1. Wood Materials

Logs of silver birch (*Betula pendula* Roth) were used in this study. The logs were freshly felled in September 2022 from Käru, Rapla County, Estonia, by the State Forest Management Centre (RMK). The logs, with a nominal length of 3 m and an average diameter of 24 cm, were visually sorted to select those with fewer knots and no signs of decay for the veneer production process.

### 2.2. Veneer Preparation

The selected logs were submerged in a soaking tank filled with water maintained at 40 °C for a duration of 48 h. Prior to the peeling, the logs were debarked, and log parameters, including core temperature, moisture content (MC), length, and annual ring width, were carefully documented.

The peeling process was conducted using an industrial-scale laboratory lathe (model 3HV66, Raute Oyj, Lahti, Finland). During peeling, the logs were processed at a speed of 60 m/min with a knife angle set to 21° and a compression rate of 10%. The logs were rotary peeled to a veneer with nominal thickness of 3.2 mm.

Once peeled, the veneers were cut into sheets (900 × 450 $mm^2$) subsequently dried in a laboratory-scale veneer dryer (Raute Oyj, Lahti, Finland) at 170 °C for 420 s. After drying, the veneers were conditioned in a controlled environment at 25 °C and 20% relative humidity (RH) at the Laboratory of Wood Technology, Tallinn University of Technology, Tallinn, Estonia. This step ensured a final MC of 5%, optimal for gluing applications.

Defect-free veneers were selected after conditioning and trimmed into smaller specimens with dimensions of 140 × 60 $mm^2$.

To account for positional effects within the log, veneers were categorized based on their location in the tree: sapwood and heartwood.

### 2.3. Densification Parameters

In this study, four pressing temperatures were selected for veneer densification process: 90 °C, 130 °C, 170 °C, and 210 °C. The lowest temperature, 90 °C, was chosen to observe the influence of equilibrium moisture content (EMC) on densification while keeping energy consumption minimal. The 130 °C hot-pressing temperature setting served as an industrial reference point, as it is commonly used in plywood production. A higher temperature of 170 °C was included to maintain a consistent 40 °C interval for trend analysis across the temperature range. Lastly, 210 °C was selected based on findings in the literature [16,17] suggesting that temperatures above 200 °C can reduce set recovery after densification due to chemical changes in lignin.

Three EMC levels were used: 5%, 12%, and 20%. The 5% EMC condition was achieved by conditioning samples at 20% RH and 25 °C and reflects standard industry preparation for birch veneers. The 12% EMC condition, representing typical service moisture levels, was obtained at 65% RH and 20 °C. Meanwhile, the high 20% EMC was created under 90% RH and 30 °C, chosen because increased moisture content lowers the glass transition temperature of lignin, improving plasticization during densification Although these values were targeted during conditioning, the actual EMC of each sample was verified post-densification using oven-dry weight measurements.

To study the role of pressing pressure in combination with wood MC and pressing temperature, three levels were applied: 1.8 MPa, 3.6 MPa, and 5.4 MPa. The 1.8 MPa pressure corresponds to standard industrial conditions for birch plywood pressing. A mid-range pressure of 3.6 MPa approaches the yield point of birch in radial compression. The highest pressure, 5.4 MPa, was designed to initiate plastic deformation within the wood structure. According to simulations by Aimene et al. [18], transverse compression of wood perpendicular to the grain reaches the plastic region near 6 MPa at 20 °C, supporting the choice of this upper pressure level. The pressing duration in this study was 8 min.

### *2.4. Standards and Methods of Analysis*

In wood densification studies, the densification ratio and compression ratio are key parameters for evaluation of the efficiency of densification treatments and to quantify the extent of material compaction.

#### 2.4.1. Densification Ratio

The densification ratio (*DR*) is defined as the percentage increase in density as a result of the densification process. It is calculated by comparing the initial and final densities of the material. Formula (1), for calculating the densification ratio, is given as:

$$DR = \frac{D_f - D_i}{D_i} \times 100 \quad (1)$$

where:

- $DR$ = Densification ratio (%);
- $D_f$ = Final density after densification (kg/m$^3$);
- $D_i$ = Initial density before densification (kg/m$^3$).

A higher densification ratio indicates a greater increase in density, which is typically associated with improved mechanical properties such as hardness, bending strength, and surface wear resistance.

#### 2.4.2. Compression Ratio

The compression ratio (*CR*) measures the reduction in thickness of the material due to applied pressing pressure during densification. It is an essential parameter for understanding the compaction behavior of wood and is expressed as a percentage decrease in thickness relative to the initial thickness. Formula (2), for calculating the compression ratio, is:

$$CR = \frac{t_i - t_f}{t_i} \times 100 \quad (2)$$

where:

- $CR$ = Compression ratio (%);
- $t_i$ = Initial thickness before densification (mm);
- $t_f$ = Final thickness after densification (mm).

The compression ratio provides valuable information about the deformation characteristics of the wood material under varying pressure and moisture content conditions.

#### 2.4.3. Effect of Moisture Content on Compression and Densification

To account for variations in initial EMC, the adjusted compression ratio is sometimes used. This approach standardizes the final thickness measurements by conditioning the samples at a controlled relative humidity (RH) and temperature after densification, ensuring consistency in comparative analysis. The adjusted compression ratio is given by Formula (3):

$$CR_{adjusted} = \frac{t_i - t_{f,adjusted}}{t_i} \times 100, \quad (3)$$

where:

- $CR_{adjusted}$ = Adjusted compression ratio (%);

- $t_i$ = Initial thickness before densification (mm);
- $t_{f,adjusted}$ = Final thickness after conditioning at standard RH (65%) and temperature (20 °C) (mm).

Conditioned veneer samples were measured for length, width, thickness, and weight using calipers and a balance to precisely determine the initial thickness and density of the wood material at 65% RH and 20 °C. Thickness measurements were also taken right before densification for each equilibrium moisture content (EMC) for different samples. The measurement points were first marked, and thickness was measured at those points to eliminate differences in thickness at different locations.

2.4.4. Densification Process

To precisely control pressure cycle, the pressure, deformation, time intervals, and pressure cycles were monitored. The non-densified veneers underwent uniaxial compression using a 50 kN universal testing machine (Zwick/Roell Z050, ZwickRoell GmbH, Ulm, Germany), and hot-pressing plates were prepared with a custom-designed controlled heating system. This system also included a cooling system using free-running cold tap water at around 10 °C.

The densification cycle was applied as follows: first, the plates were heated to the target densification temperature, then a preload of 5 N was applied, followed by the increase in pressure until the target values and continuing the densification process for 8 min. During the cooling phase, heating was turned off, and tap water was introduced to cool the plates. The temperature was reduced below 40 °C and maintained under load at the same pressure for 5 min. After this, the sample was removed, and length, width, and thickness were measured again from the marked points.

The densified samples were then conditioned at 65% RH and 20 °C. Thickness measurements for each densified sample were taken under these conditions to eliminate the effect of different EMCs and thickness variations that could introduce errors in the densification ratio for both thickness and density.

Specimen dimensions were measured following European Standard EN325:2012 [19] after conditioning at 20 ± 2 °C and 65 ± 5% RH. Thickness measurements adhered to EN315:2002 [20], while density determinations were conducted as per EN323:2002 [21]. All density measurements were taken after conditioning specimens at a RH of 65 ± 5% and a temperature of 20 ± 2 °C. The moisture contents of samples were measured according EN13183-1 [22].

## 3. Results and Discussion

### *3.1. Density and Densification Ratio*

The densification process led to notable increases in density across all combinations of temperature, pressure, and EMC. Table 1 summarizes the density results before and after densification. The highest final density, 1028 kg/m$^3$, was achieved at 90 °C, 5.4 MPa, and 20% EMC, closely followed by 954 kg/m$^3$ at 210 °C and 5.4 MPa with the same EMC. A previous study [2] reported that the density of densified wood is influenced by the applied pressure and temperature during the densification process, as well as the wood species used. Similar trends were observed in our study. For instance, in the referenced literature, using birch veneer with an initial EMC of 5%, a densification temperature of 200 °C, and pressing pressure of 12 MPa, a final density of 963 kg/m$^3$ was achieved. In comparison, our study, using birch veneer and the initial EMC (5%) but with a temperature of 210 °C and a lower pressing pressure of 5.4 MPa resulted in a final density of 941 kg/m$^3$. This demonstrates that our results are quite comparable despite the significantly lower applied pressure. In contrast, the lowest final density, 565 kg/m$^3$, occurred at 170 °C, 1.8 MPa, and 5% EMC. These results suggest that high EMC combined with elevated pressure significantly enhances wood plasticization and compressibility, particularly at 90 °C and 210 °C. Even at low temperatures, high EMC can sufficiently soften the wood matrix for effective densification.

**Table 1.** Initial and final densities of veneer samples before and right after densification; values in parentheses show the standard deviations.

| **Temperature** | **5% EMC** | | **12% EMC** | | **20% EMC** | |
|---|---|---|---|---|---|---|
| **Pressure, MPa** | **Initial Density, kg/m$^3$** | **Final Density, kg/m$^3$** | **Initial Density, kg/m$^3$** | **Final Density, kg/m$^3$** | **Initial Density, kg/m$^3$** | **Final Density, kg/m$^3$** |
| **90 °C** | | | | | | |
| 1.8 MPa | 551 (49) | 572 (45) | 562 (46) | 598 (42) | 583 (57) | 751 (36) |
| 3.6 MPa | 562 (52) | 607 (42) | 564 (56) | 687 (48) | 583 (51) | 948 (82) |
| 5.4 MPa | 541 (45) | 624 (31) | 563 (51) | 900 (50) | 567 (71) | 1028 (77) |
| **130 °C** | | | | | | |
| 1.8 MPa | 564 (49) | 582 (45) | 580 (51) | 593 (43) | 582 (44) | 617 (23) |
| 3.6 MPa | 557 (56) | 601 (52) | 571 (54) | 621 (49) | 583 (60) | 652 (52) |
| 5.4 MPa | 549 (46) | 635 (25) | 574 (55) | 699 (36) | 584 (58) | 728 (14) |
| **170 °C** | | | | | | |
| 1.8 MPa | 544 (36) | 565 (44) | 562 (50) | 579 (37) | 571 (45) | 589 (42) |
| 3.6 MPa | 563 (58) | 604 (51) | 547 (63) | 603 (45) | 591 (51) | 620 (39) |
| 5.4 MPa | 563 (40) | 644 (18) | 561 (44) | 671 (17) | 590 (54) | 679 (21) |
| **210 °C** | | | | | | |
| 1.8 MPa | 557 (50) | 622 (45) | 569 (42) | 621 (25) | 585 (44) | 628 (21) |
| 3.6 MPa | 562 (60) | 764 (35) | 564 (76) | 767 (21) | 573 (51) | 800 (37) |
| 5.4 MPa | 562 (54) | 941 (31) | 549 (44) | 940 (50) | 589 (48) | 954 (36) |

The densification ratio showed a clear dependence on temperature, pressure, and EMC (Figure 1). At 90 °C, the highest ratio of 84.4% was obtained at 5.4 MPa and 20% EMC. Densification tests were conducted using saturated steam at temperatures ranging from 140 °C to 220 °C, and pressures between 4.5 and 9 MPa on aspen and hybrid poplar achieved compression ratios approaching 100% [3], which is higher than the results obtained in this study, likely due to the lower initial density of aspen compared to the birch used in this study. Lower values were seen at intermediate temperatures like 130 °C and 170 °C, except for 5.4 MPa and 5% EMC at 130 °C. For instance, at 130 °C and 12% EMC, the ratio dropped to 22.8%, while at 90 °C and the same pressure and EMC, it reached 61.1%. However, at 210 °C, the densification ratio increased again, reaching 72.4% under 5.4 MPa and 12% EMC, even though wood moisture content is almost entirely lost (e.g., from 11.6% to 0.2% at 3.6 MPa) (see Table 2). This can be attributed to the fact that this temperature exceeds the lignin glass transition point, allowing for structural rearrangement of the wood matrix despite the low moisture content, leading to high densification levels. Thus, despite excessive moisture loss, the structural softening at high temperatures compensates for the reduction in compressibility. These variations are strongly influenced by the change in EMC during pressing, Table 2 and Figure 1 show that the relationship between pressure and densification is not entirely linear across all temperatures and EMC levels. However, at the same temperature and EMC, higher pressure results in greater densification. The same trend applies to increasing EMC at constant pressing pressure and temperature. The difference in final veneer densities between 210 °C and 90 °C may result from moisture loss at higher temperatures. The veneer samples densified at 210 °C are almost completely dry, while those at 90 °C retain some moisture. For instance, under the condition of 90 °C, 5.4 MPa, and an initial EMC of 20%, the final EMC after densification was still 16.6%, indicating that a significant amount of moisture remained in the veneer post-compression.

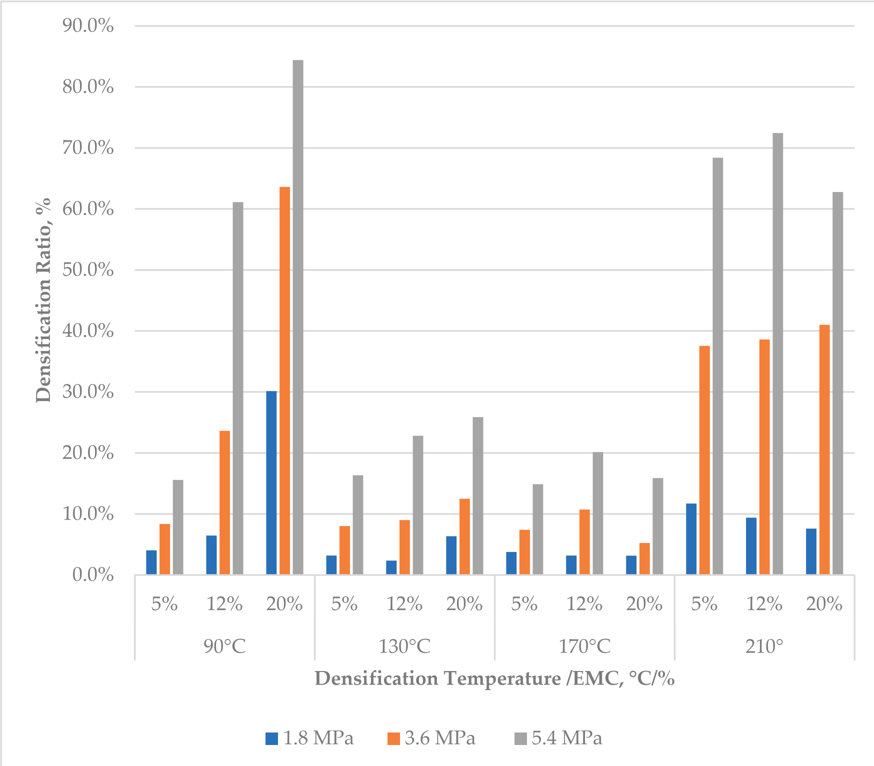


**Figure 1.** Densification ratios of veneer samples.

Error bars are not included in Figures 1–4 due to significant variability introduced by the use of three different logs, each with distinct average densities: 520 $kg/m^3$ for Log 1, 634 $kg/m^3$ for Log 2, and 538 $kg/m^3$ for Log 3. While the standard deviation appears high when calculated using the overall dataset, this variation primarily reflects the natural density differences between logs rather than inconsistency in the densification process itself. For instance, under the condition of 90 °C, 5.4 MPa, and 20% EMC in Figure 1, the densification ratio showed a standard deviation of 30.4% when all logs were averaged. However, when calculated within individual logs, the deviation for the same condition dropped significantly to just 4.6%. Similar trends are observed across Figures 2–4. Therefore, including error bars based on the total dataset might give a misleading impression of process instability, whereas the actual variation lies in the inherent biological differences between logs. To avoid misinterpretation and preserve clarity, error bars are omitted from these figures. The focus is instead on illustrating general trends across pressing parameters.

These results confirm that combining high pressing pressure with increased EMC and moderate to high temperatures enhances densification. Higher initial moisture contributes to greater densification efficiency at lower temperatures, whereas excessive moisture loss reduces compressibility. For example, at 130 °C and 5.4 MPa with 12% EMC, the densification ratio was 22.8%, while at 90 °C under the same conditions, it was 61.1%. At 210 °C, densification ratios increased again, especially under higher pressures, reaching 72.4% at 5.4 MPa and 12% EMC. This is attributed to thermal softening of lignin [5] and hemicellulose, facilitating deformation under low EMC. Notably, densification at 90 °C and 5.4 MPa also yielded strong results, especially at high EMC, with a ratio of 84.4%. This suggests that although extreme temperatures such as 210 °C can lead to higher densification even with moisture loss, the performance of veneers at 90 °C is significantly higher ($p$ = 0.016), while allowing for more controlled changes in EMC.

**Table 2.** Initial and final EMC of veneer samples right before and right after densification.

| Temperature | 5% EMC | | 12% EMC | | 20% EMC | |
|---|---|---|---|---|---|---|
| **Pressure** | **Initial EMC, %** | **Final EMC, %** | **Initial EMC, %** | **Final EMC, %** | **Initial EMC, %** | **Final EMC, %** |
| **90 °C** | | | | | | |
| 1.8 MPa | 5.2 | 4.6 | 9.6 | 9.1 | 17.9 | 16.5 |
| 3.6 MPa | 5.0 | 4.5 | 9.3 | 9.1 | 17.8 | 16.6 |
| 5.4 MPa | 5.0 | 4.5 | 9.9 | 9.5 | 17.5 | 16.6 |
| **130 °C** | | | | | | |
| 1.8 MPa | 5.0 | 2.2 | 11.8 | 2.6 | 17.8 | 2.6 |
| 3.6 MPa | 4.9 | 2.5 | 10.5 | 2.4 | 17.6 | 2.6 |
| 5.4 MPa | 4.8 | 2.3 | 10.3 | 2.5 | 17.6 | 2.6 |
| **170 °C** | | | | | | |
| 1.8 MPa | 5.4 | 0.7 | 12.0 | 0.4 | 17.2 | 0.8 |
| 3.6 MPa | 5.0 | 0.7 | 11.6 | 0.6 | 17.3 | 0.8 |
| 5.4 MPa | 5.0 | 0.7 | 10.6 | 0.6 | 17.6 | 0.6 |
| **210 °C** | | | | | | |
| 1.8 MPa | 5.9 | 0.3 | 11.8 | 0.3 | 17.5 | 0.5 |
| 3.6 MPa | 5.8 | 0.4 | 11.6 | 0.2 | 17.6 | 0.2 |
| 5.4 MPa | 5.9 | 0.3 | 11.7 | 0.2 | 17.7 | 0.3 |

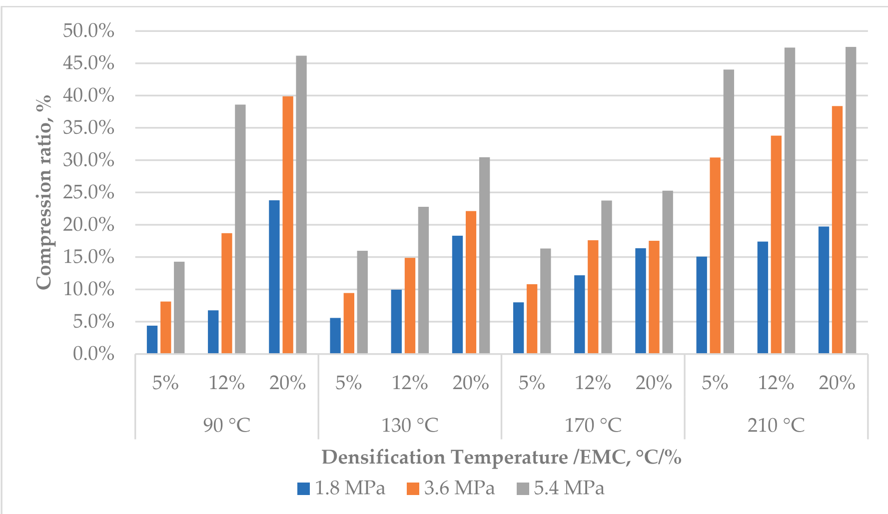


**Figure 2.** Compression ratios after densification calculated before and after densification.

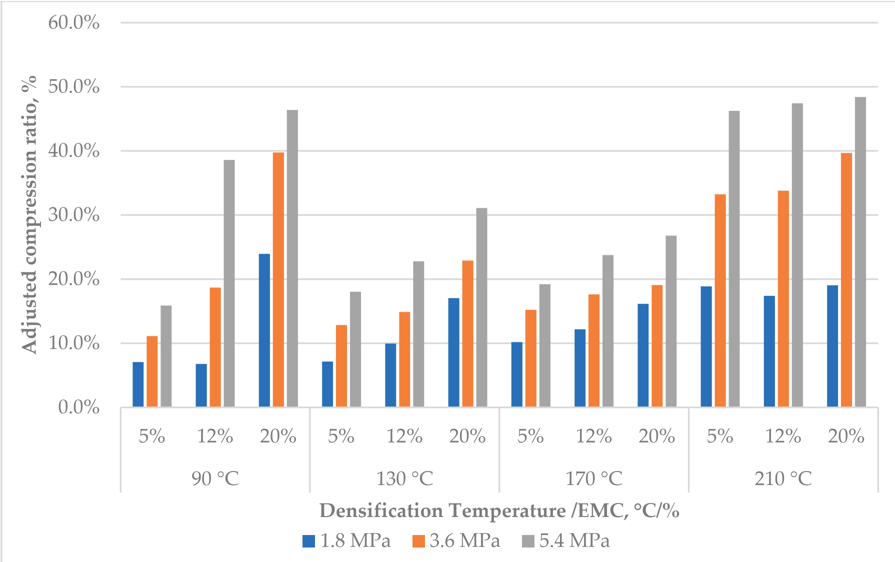


**Figure 3.** Adjusted compression ratio taken for all samples' initial thickness at 20 °C and 65%RH.

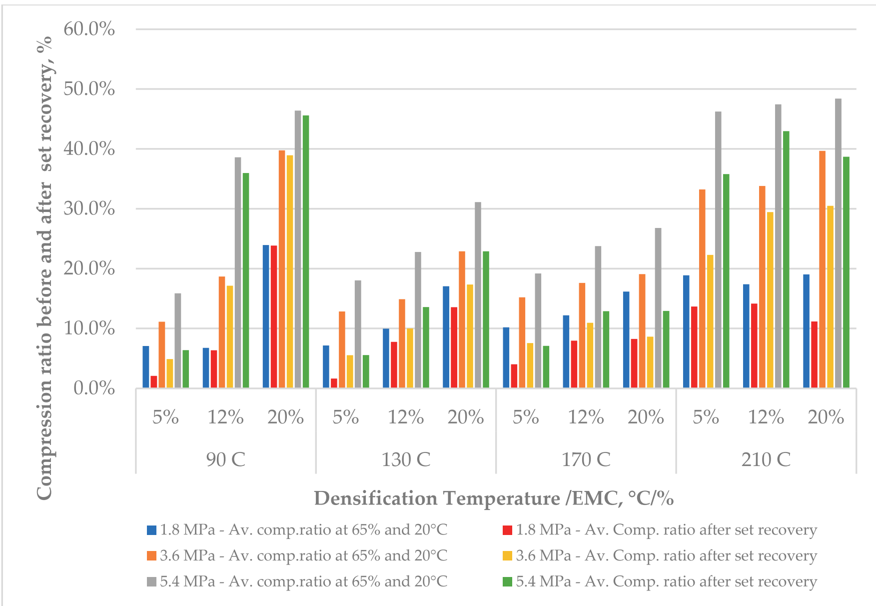


**Figure 4.** Compression ratios of densified samples before and after set recovery.

Comparing 90 °C and 210 °C at different pressures, both achieved high final densities. However, considering industrial scalability, energy efficiency, and environmental sustainability, 90 °C appears more suitable. Lower energy consumption at this temperature makes it favorable for large-scale processes.

In summary, while high temperatures (e.g., 210 °C) can achieve substantial densification despite moisture loss, 90 °C offers a more balanced approach, ensuring effective densification with manageable moisture changes and lower energy use.

At atmospheric pressure and 90 °C, densification efficiency was relatively high, especially at low pressures, likely due to minimal moisture loss. EMC values before and after densification show only slight reductions, allowing the wood to retain plasticity and achieve higher final densities.

At 130 °C and 170 °C, densification efficiency dropped despite higher pressures. This may be due to substantial moisture loss, as seen in Table 2. For example, at 130 °C and 3.6 MPa, EMC decreased from 10.5% to 2.4%, and at 170 °C and 1.8 MPa, from 12% to 0.4%. This limits plasticization and reduces densification efficiency, resulting in lower final densities compared to 90 °C under similar conditions.

*3.2. EMC Change During Pressing*

The change in EMC during hot pressing offers critical insight into the moisture-dependent plasticization of wood. As shown in Table 2, at 90 °C, EMC remained relatively stable due to lower thermal heating energy used, allowing the wood to retain its moisture content and maintain high compressibility. In contrast, at 130 °C, EMC dropped from 10.5% to 2.4%, and at 170 °C, from 12% to 0.4%. This substantial moisture loss diminished the softening effect of water within the wood structure, reducing densification efficiency.

Notably, at 210 °C, despite a significant EMC decrease, veneer densification improved. This suggests that at elevated temperatures, thermal softening of lignin and hemicellulose can compensate for moisture loss. Therefore, densification at 210 °C may depend more on heat-induced plasticization than on moisture content.

*3.3. Compression Ratio and Adjusted Values*

The compression ratio was evaluated under varying conditions of temperature, pressure, and initial equilibrium moisture content (EMC). Results are summarized in Figure 2, which categorizes compression ratios by initial EMC, and Figure 3, which presents values adjusted for initial thickness at standardized conditions (65% RH, 20 °C) immediately after compression.

Compression ratio analysis confirmed a strong dependence on pressing pressure and EMC. At 90 °C pressing temperature, compression ratio values ranged from 4.4% at 1.8 MPa and 5% EMC to 46.2% at 5.4 MPa and 20% EMC. At 210 °C, the compression ratio peaked at 47.5% under 5.4 MPa pressure and 20% EMC, with a minimum of 15.1% at 1.8 MPa and 5% EMC. The enhanced densification at 210 °C is likely due to increased plasticity of the wood matrix above the lignin glass transition temperature, which promotes deformation under pressure. In a previous study [2], birch veneers with an initial EMC of 5% were densified at three temperatures (100 °C, 150 °C, and 200 °C) using pressure levels of 4, 8, and 12 MPa. The results demonstrated that densification temperature and pressure had statistically significant effects on veneer thickness and compression ratio (CR). It was observed that CR increased with both temperature and pressure, reaching a maximum of 40% at 200 °C and 8 MPa, while the lowest CR was 7% at 200 °C and 4 MPa. Notably, there was no significant change between 100 °C and 150 °C in terms of thickness reduction, but a substantial change was seen at 200 °C, attributed to the softening of wood at higher temperatures. These findings are in good agreement with our results, where CR values ranged from 8.1% (5% EMC, 90 °C, 3.6 MPa) to 44% (5% EMC, 210 °C, 5.4 MPa), confirming a similar trend in which higher temperature and pressure led to greater densification in birch veneer.

Initial EMC had a notable influence: higher EMC values (20%) consistently led to greater compression ratios, whereas lower EMC (5%) resulted in reduced compressibility. This reinforces the role of moisture as a plasticizer. In contrast, intermediate temperatures such as 130 °C and 170 °C were less effective due to excessive moisture loss, which limited the softening effect of water within the wood fibers.

When compression ratios were adjusted for standardized conditions (see Figure 3), slightly higher values were observed across all cases. The highest adjusted compression ratio was 48.4% at 210 °C and 5.4 MPa. These adjusted values were especially higher at elevated temperatures, emphasizing how post-densification conditions can affect the interpretation of compression efficiency.

### 3.4. Thickness Reduction and Set Recovery

Thickness measurements confirmed that densification consistently reduced veneer thickness. The most significant reduction occurred at 210 °C and 5.4 MPa, with a decrease from 3.39 mm to around 1.70 mm for high EMC samples. A similar reduction was seen at 90 °C and 5.4 MPa with 20% EMC, where thickness dropped from 3.39 mm to 1.86 mm.

In this study, set recovery was evaluated after densification by placing the samples into conditions of 65% relative humidity (RH) and 20 °C, which varied with densification parameters (see Figure 4). The lowest set recovery occurred at 90 °C, 20% EMC, and 1.8 MPa, indicating stable compaction and long-term thickness retention. In contrast, the highest set recovery was observed in veneer samples densified at 170 °C, 5.4 MPa, and 20% EMC, suggesting greater susceptibility to post-densification expansion.

When comparing veneers densified 90 °C and 210 °C at 5.4 MPa and 20% EMC, set recovery was lower at 90 °C, despite both achieving high compression ratios.

Due to the nature of the densification process and the equipment used, determining the immediate post-densification thickness was challenging. Since the densification process was conducted without mechanical stoppers, the samples were compressed freely until reaching their final thickness under the applied pressing temperature, EMC, and pressing pressure conditions.

Final densified veneer thicknesses measured after conditioning demonstrated that some degree of set recovery occurred across all pressing temperatures, EMC levels, and pressures. However, samples densified at lower temperatures and higher EMC—particularly at 90 °C, 20% EMC, and 1.8 MPa—exhibited the least recovery, retaining most of their compressed form. Conversely, higher set recovery at 130 °C and 170 °C and 5.4 MPa suggests greater sensitivity to humidity in those conditions.

These findings emphasize that pressing temperature, EMC, and pressure jointly influence the post-densification stability of veneers. Tao Li et al. [23] conducted a study to optimize parameters for Chinese fir wood densification, including densification temperature (140 °C, 155 °C, and 170 °C, which are comparable to our 130 °C and 170 °C), densification duration (10, 20, and 30 min), and post-densification heat treatment temperature (170 °C, 185 °C, and 200 °C). They reported that set recovery was significantly influenced by the densification temperature and heat treatment temperature, while the duration of densification had no significant effect—findings that are consistent with our results regarding the influence of temperature on set recovery. However, a key difference between their findings and ours is the direction of the effect: in our study, set recovery increased with higher densification temperature (from 130 °C to 170 °C), whereas Tao Li et al. observed a decrease in set recovery with increasing temperature. This discrepancy may be attributed to differences in the duration of densification and heat treatment parameters used in their study. Moreover, they did not report the pressing pressure applied during densification, nor did they investigate the influence of different EMC levels, both of which are critical factors considered in our research. Notably, they concluded that heat treatment was the most influential factor affecting set recovery, which could further explain the divergence in results. Densification at lower temperatures with adequate moisture levels can lead to more stable thickness retention after reconditioning, an important factor for industrial applications where long-term performance is essential.

### 3.5. Industrial Relevance and Optimization

From an industrial perspective, densification at 90 °C and 5.4 MPa with 20% EMC offers a favorable balance of higher compression ratio, low energy consumption, and superior thickness retention. Although veneer densification at 210 °C produced the highest compression ratios, it also involves greater energy demand and increased risk of thermal degradation and emissions, raising concerns over environmental and material sustainability.

The results confirmed that veneer densification process optimization requires careful combination of pressing temperature, pressure, and EMC parameters. High EMC enhances compressibility at lower temperatures, while high temperatures can offset moisture loss through thermal softening of wood polymers. Elevated pressure further amplifies densification efficiency. Understanding these interactions is crucial for developing energy-efficient and sustainable veneer densification processes.

Comparing the results at 90 °C and 210 °C, compression ratios achieved at 90 °C under 5.4 MPa closely approach those at 210 °C, especially at higher EMC levels (see Figure 3). However, the lower thermal load at hot pressing in 90 °C significantly reduces energy consumption, limits thermal degradation of wood, and minimizes emissions, offering a more sustainable and cost-effective solution for industrial-scale production.

It should also be noted that when comparing set recovery values at 90 °C and 210 °C, the moisture conditions during reconditioning differ significantly (see Table 2). At 210 °C, EMC drops to nearly zero, and reconditioning at 65% RH and 20 °C brings the EMC back up to approximately 12%, resulting in a large moisture change. In contrast, at 90 °C and 5.4 MPa with 20% initial EMC, the moisture loss is only around 1%, and the final EMC after densification remains at 16.5%. Reconditioning under the same conditions would therefore involve a much smaller moisture increase of only 4.5%. This distinction is important, as set recovery is influenced not only by mechanical compaction but also by the extent of moisture regain and should be interpreted with these moisture dynamics in mind.

## 4. Conclusions

This study explored the systematic investigation of the combined effects of pressing temperature, pressure, and equilibrium moisture content (EMC) on the densification performance of rotary-cut birch veneers. The densification process significantly influenced key physical properties, including final density, densification ratio, compression ratio, and set recovery. The following conclusions can be drawn based on the findings:

Increasing pressing pressures (up to 5.4 MPa) consistently improved final density and compression ratios of wood veneers, particularly when combined with higher initial EMC levels (12% and 20%). Veneers with 20% EMC achieved the highest densification ratios, especially at 90 °C and 210 °C. This confirms that sufficient moisture content enhances the plasticization of the wood matrix, leading to improved compaction.

At lower temperatures (90 °C), densification was highly efficient when paired with high EMC and pressure, resulting in final densities up to 1028 kg/m$^3$ and densification ratios over 84%. At intermediate temperatures (130 °C and 170 °C), excessive moisture loss during pressing limited plastic deformation and reduced compaction. At 210 °C, despite near-total moisture loss, the thermal softening of lignin and hemicellulose enabled effective densification under higher pressure. However, to maintain moisture-assisted plasticization at high temperatures, pressing must be rapid. Quick loading allows compaction to occur before moisture escapes; otherwise, slower loading leads to EMC reduction and diminished compressibility.

The most stable thickness retention after reconditioning (65% RH, 20 °C) was observed at 90 °C with 20% initial EMC. Importantly, moisture conditions during reconditioning significantly affect set recovery outcomes. At 210 °C, the EMC after pressing drops to nearly zero, and reconditioning induces a ~12% moisture regain, leading to larger thickness recovery. In contrast, at 90 °C and 5.4 MPa with 20% initial EMC, the final EMC after densification is still 16.5%, and reconditioning involves only a 4.5% decrease, resulting in lower set recovery. This demonstrates that set recovery is influenced both by mechanical and hygroscopic changes, and must be interpreted within the context of actual moisture change during reconditioning.

Higher EMC values generally led to greater compression ratios. The maximum compression ratio of 47.5% was obtained at 210 °C, 5.4 MPa, and 20% EMC. When adjusted to standardized conditions (65% RH, 20 °C), compression ratios increased further, affirming the importance of both pressure and moisture in maximizing deformation and densification.

Although 210 °C provides high densification even with low residual moisture, the 90 °C condition under high EMC and pressure offers a better trade-off between performance, energy efficiency, and environmental impact. Lower-temperature processing reduces thermal degradation risks, minimizes emissions, and enables more stable dimensional retention after reconditioning, making it highly favorable for sustainable, large-scale wood veneer densification.

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