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ORIGINAL

Effect of chemical and thermal modification, and material replacement on strand board properties

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Abstract

The purpose of this paper was to analyze the effects of various OSB-strand modifications on physical and mechanical properties of strand board. Norway spruce (*Picea abies* L. Karst) strands were acetylated using acetic anhydride or thermally modified at 180 °C using atmospheric pressure and superheated steam environment. Strand boards made of acetylated strands (Acet), thermally modified strands (TM) and thermally modified strands used only at surface layers (TM_{SL}) were produced. Furthermore, strand boards with 20% ($Cork_{20\%}$) and 40% ($Cork_{40\%}$) cork particles were manufactured. Wood-water relations, i.e., equilibrium moisture content (EMC), water absorption (WA), thickness swelling (TS), as well as mechanical properties, i.e., bending strength and internal bonding, were tested and compared to untreated reference strand board. The EMC for TM_{SL} was no different than the reference boards, however, the other boards had a statistically significant decrease in EMC. Acetylated strand board and boards with cork particles had a significant increase in water resistance. The mechanical properties decreased for TM and $Cork_{40\%}$, but no difference was shown for $Cork_{20\%}$. Acetylation increased internal bond strength. The results provide a comparison between different modifications of strand boards and show a new possibility of reducing the water effects on OSB with cork particles.

1 Introduction

Oriented strand board (OSB) is an engineered wood-based panel for various applications. It is a sheet material made of wooden strands bonded with synthetic resin. OSB is typically made of three layers, with surface strands oriented in the perpendicular direction to the core layer. Global sales of OSB were estimated around 32 million cubic meters in 2018 (Absolute Reports 2019).

Wood as an important renewable and low-cost material is widely used for various applications, for example furniture production and building construction. Solid wood properties are influenced by water absorption that might limit the range of feasible applications. Dimensional stability of OSB depends on the wood species, sizes of particles, type of adhesive, etc. One way of increasing dimensional stability of OSB is modification of the board, such as modification of the strands (thermal modification, acetylation) or replacing parts of strands by different particles (plastics, cork). Wood modification techniques can be applied in order to improve certain wood properties, for example, bio-durability, dimensional stability, colour, wettability, etc. (Hill and Jones 1996; Militz 2002; Rowell 1983; Hill 2006; Čermák et al. 2015; Dömény et al. 2015).

A widely used modification of wood is thermal modification, which involves application of heat to the wood at temperatures normally between 160 and 260 °C in a controlled environment, depending on the desired degree of modification. Thermal modification of wood at high temperatures leads to chemical modifications of hemicelluloses, cellulose and lignin (Sandermann and Augustin 1963a, b, 1964; Kollmann and Fengel 1965; Fengel and Wegener 1989; Tjeerdsma et al. 1998). The degradation starts with deacetylation, and the release of acetic acid acts as a depolymerization catalyst, which further increases polysaccharide decomposition. At the same time, hemicelluloses, which are the most affected constituents, undergo dehydration reactions associated with a decrease in hydroxyl (OH–) groups (Tjeerdsma et al. 1998; Sivonen et al. 2002). In addition,

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cellulose crystallinity increases due to degradation of the amorphous part of cellulose. Furthermore, new extractive compounds emerge from wood as a by-product of degradation, which participate in cross-linking in lignin. The amount and accessibility of the OH-groups is reduced, leading to less interaction between wood and water, reduction in wood EMC, and consequently improved dimensional stability (Militz 2002; Hill 2006).

Two possibilities of thermal modification for OSB are the pre-treatment of strands and post-treatment of the boards. Thermal modification has been demonstrated to increase durability and dimensional stability, whereas density and mechanical properties were reduced, and the color shifted towards darker tones (Esteves and Pereira 2008; Candelier et al. 2016; Mendes et al. 2013). The reduction in moisture content, water absorption and thickness swelling, even if associated with decreasing IB, MOR and MOE of thermally treated OSB, has been observed (Boonstra and Tjeerdsma 2006; Cetera et al. 2018; Mohebby et al. 2008; Paul and Ohlmeyer 2005; Paul et al. 2006; Pétrissans et al. 2003; Goroyias and Hale 2002; Mendes et al. 2013).

Another type of modification is by chemical methods. Chemical modification can be used as an efficient way to transform hydrophilic OH groups into larger hydrophobic groups (Kollmann 1951; Skaar 1988; Bodîrlău et al. 2009). The basic types of chemical modification use simple monofunctional modifying agents. One of the most practical is the reaction known as acetylation (Rowell 1983). Acetylation effectively changes free hydroxyls within the wood into acetyl groups, which improve the dimensional stability and biological durability of wood (Rowel 1983; Hill and Jones 1996; Larsson and Simonsons 1994; Popescu et al. 2013; Dömény et al. 2015). The most common reagent used for acetylation is acetic anhydride (Ac_2O), which reacts with wood hydroxyls, with or without a catalyst, forming wood ester and releasing acetic acid in the wood structure. The standard acetylation process includes impregnation of oven-dried wood with Ac_2O, followed by conventional heating to initiate the chemical reactions with wood polymers (Bongers and Beckers 2003; Dömény et al. 2015). Acetic acid is then released as a by-product of the reactions (Homan and Jorissen 2004). Apart from loss of almost 50 percent of the reagent, the entrapped acid is a nuisance as it emits odor and is corrosive to metal fasteners (Koppers 1961; Otlesnov and Nikitina 1977). It has been found that this treatment retains the original colour of wood and improves wood-water related properties, biological durability, strength, acoustic and dielectric properties (Tarkow et al. 1950; Dreher et al. 1964; Militz 1991; Homan et al. 2000).

Another method to improve dimensional stability of the OSB is to replace parts of the wood component by other components. The research by Klímek et al. (2016) on particleboard with PET particles reduced thickness swelling from 20 to 10%. Cork is a widely used natural material because it is lightweight, elastic, flexible, has good thermal, vibrational and acoustic insulating characteristics, has a high friction coefficient, is impermeable to liquids, chemically stable and fire resistant (Carmo Lança et al. 2006; Gil 2009; Gil and Moiteiro 2003; Gill and Silva 2004; Rosa and Fortes 2007). When added to particleboards, cork could cause reduction in thickness swelling because the diffusion of water in cork is very slow compared to the diffusion of water in wood.

A critical component of OSB is the resin. Three main resins, singular and in combination, are used for OSB production: phenol–formaldehyde, melamine-urea–formaldehyde, and isocyanate (pMDI). There are advantages and disadvantages for each resin. Two advantages of pMDI are its ability to wet nonpolar surfaces and potentially react with hydroxyl groups in wood furnish to form irreversible urethane linkages (Pizzi and Mittal 1994). Isocyanate-bonded composite panels are characterized by water-resistant chemical bonds, strong mechanical bonds, toughness, low resin dosage, and good moisture resistance (Papadopoulos 1999). Deep penetration of the isocyanate resin into wood may repair weak zones created during the modification of wood (high temperature, soaking in Ac_2O). The isocyanate resin system is more suitable for the use in boards made from modified raw material than the formaldehyde resin system (Papadopoulos et al. 2006).

The present study aims to analyze modification techniques of OSB, evaluate the efficacy of modification process (mass loss, uptake of chemical) and evaluate material properties (density and density profile, equilibrium moisture content, thickness swelling, water absorption, bending strength and internal bonding). This work should provide a better insight into the potential benefits of the OSB modification process.

2 Materials and methods

Norway spruce (*Picea abies* L. Karst) strands were made in the industrial production of OSB in the Czech Republic. The initial moisture content before modification was between 2 and 6% as determined by the oven-dry method of standard EN 13183-1 (2002). The dimensions of the strands were thickness 0.6–1.2 mm, width 20–40 mm and length 90–120 mm.

2.1 Thermal modification of wood strands

Strands were oven-dried at 103 ± 2 °C before thermal modification to achieve 0% moisture content. The batch of dry strands was then weighed. The strands were further thermally modified at 180 °C in a laboratory chamber using atmospheric pressure and superheated steam environment.

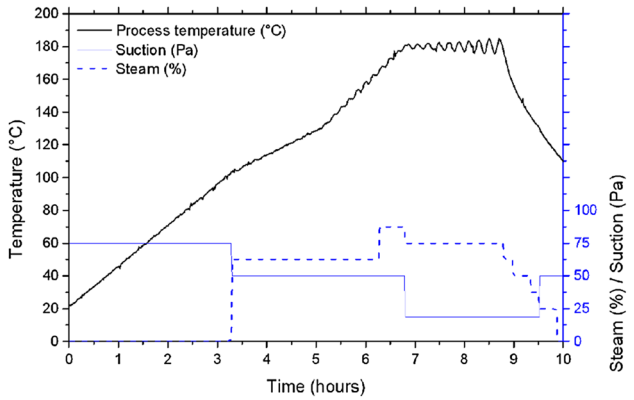

Fig. 1 Time-temperature diagram of thermal modification of wood strands for OSB manufacturing

The maximum temperature (180 °C) was maintained for 2 h (Fig. 1). The degree of modification was determined by mass loss (M_L), based on the oven-dry batch mass before and after thermal modification. M_L was calculated according to Eq. (1).

$$\text{Mass loss}\ (\%) = \left(m_{u,[O.D.]} - m_{m,[O.D.]}\right) / m_{u,[O.D.]} \times 100, \quad (1)$$

where $m_{m,[O.D.]}$ is the oven-dry mass of the batch after modification and $m_{u,[O.D.]}$ is the oven-dry mass of the batch before modification.

2.2 Acetylation of strands

Strands were oven-dried at a temperature of 103 ± 2 °C before acetylation to 0% moisture content. Afterward the strands were soaked in Ac_2O (Sigma-Aldrich, analytical grade ≥ 99%) for 72 h. The weight percentage gain (WPG) was used as an indicator of substance uptake according to the following formula Eq. (2),

$$\text{Weight percent gain}\ (\%) = \left(m_2 - m_1\right) / m_1 \times 100, \quad (2)$$

where m_1 is the strand weight before soaking and m_2 is the strand weight after soaking, chemical reaction and vacuuming (removing residuals).

Once soaking took place, the conventional heating at a temperature of 90 ± 2 °C for 60 min was used in order to induce chemical reactions with wood polymers. At the end of the acetylation process, the strands were placed into the autoclave in vacuum at 10 kPa for 120 min to eliminate the residual acetic anhydride and acetic acid from the wood structure. Uptake of the substance was determined in three steps: after soaking, after chemical reaction and after vacuum treatment when residuals were eliminated.

2.3 Cork particles

Cork particles used for the experiment (Amorim & Irmãos, S.G.P.S., S.A., Portugal) had a density of 160–260 kg/m^3. Cork particles were sorted for size fraction greater than 1 mm and less than 3.15 mm. These cork particles were used to replace a part of the strands in the strand board. One board with 20% of cork particles and one board with 40% of cork particles by weight were produced.

2.4 Production of boards

Strand boards were produced in the laboratory. The resin was applied on the strands with an air-atomization sprayer in a rotary blender. The pMDI resin Ongronat W0 2750 (BorsodChem Zrt., Hungary) was used, with a density of resin 1.23 g/cm^3 and viscosity 170–230 MPa s. The boards were pressed with 5% of adhesive and 0.6% of paraffin emulsion based on oven-dry weight. Target density of the board was 600 kg/m^3. Strand mats were formed by hand without orientation. The moisture content of the strands before pressing was 4%. The mat of strands, 600 mm × 600 mm, was pressed to a thickness of 12 mm at a temperature of 180 °C for 120 s. The press closing time was 15 s, followed by compression pressure held constant at 5 MPa for 100 s; then reduced to 2.5 MPa for 10 s, and finally reduced to 1 MPa for 10 s before opening the press. Six boards were manufactured: one reference board without modification of strands (Ref), 1 board with 100% of thermally modified strands (TM), 1 board with 12% by volume of thermally modified strands on each surface layer (TM_{SL}), one board with acetylated strands (Acet), one board with 20% of cork particles ($Cork_{20\%}$) and one board with 40% of cork particles ($Cork_{40\%}$). The boards were cut into the test specimens (Fig. 2). There were five groups of specimens: one bending properties; two density,

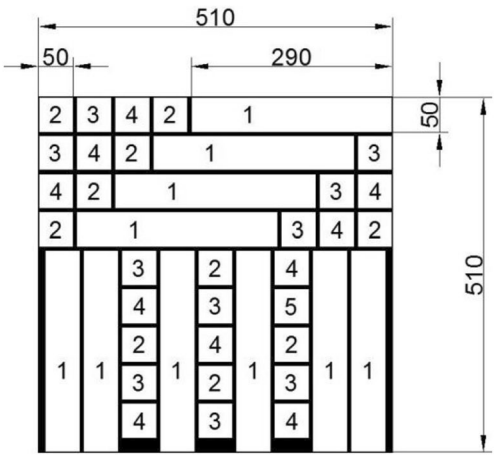

Fig. 2 Cutting plan for test specimen production (dimensions in mm)

moisture content, water absorption, thickness swelling at 99% RH; three thickness swelling after soaking; four internal bonding; five density profile.

3 Testing procedures

3.1 Density and density profile

Density was determined according to the methodology in EN 323 on 10 specimens from each board.

Further, the density profile was measured from one specimen from each board. The specimens with dimensions of $50 \times 50 \times 12$ mm^3 (conditioned at 20 °C and 65% RH) were measured at an interval of 0.01 mm through the sample thickness (12 mm) using an X-ray densitometer (X-ray, Dense-Lab).

3.2 Wood–water relations

Moisture content was determined according to the methodology in EN 322 on 10 specimens with dimensions of 50×50 mm^2. Specimens were conditioned at a temperature of 20 °C and relative humidity of 65%.

Water absorption and thickness swelling were measured on ten specimens with dimensions 50×50 mm^2 that were oven-dried at a temperature of 103 ± 2 °C. The weight and thickness of the specimens were measured after drying. The specimens were then supported by a wire mesh above water inside a closed plastic box to achieve approximately 99% relative humidity. The weight and thickness of specimens were measured after 2, 24, 48, 168 (1 week), 336 (2 weeks), 504 (3 weeks), and 672 h (4 weeks). Water absorption is an indicator of water uptake of the strand board.

$$\text{Water absorption } (\%) = \left(W_{[W]} - W_{[O.D.]}\right) / W_{[O.D.]} \times 100, \quad (3)$$

where $W_{[W]}$ is weight of the wet specimen, and $W_{[O.D.]}$ is weight of the oven-dried specimen.

$$\text{Thickness swelling } (\%) = \left(t_2 - t_1\right) / t_1 \times 100, \quad (4)$$

where t_1 is the thickness before soaking/99% RH and t_2 is the thickness after soaking/99% RH.

Thickness swelling after soaking was realized according to EN 317 on ten specimens with dimensions 50×50 mm^2. The thickness of the conditioned specimens at a temperature of 20 °C and relative humidity of 65% was measured after conditioning. The specimens were fully immersed in water at a temperature of 20 °C. The thickness of the specimens was measured in the center of the sample after 2, 24, 48 and 168 h (1 week).

3.3 Bending properties and internal bonding

Mechanical testing was carried out on a Zwick®Z050 universal testing machine with testXpert v11.02 software and a 50 kN load cell (Zwick GmbH & Co. KG, Ulm, Germany). Specimens were tested after conditioning at a temperature of 20 °C and relative humidity of 65%.

Three-point bending tests (EN 310) were conducted to determine modulus of elasticity (MOE) and modulus of rupture (MOR) on ten specimens with dimensions 290×50 mm^2. The specimens were loaded with a loading rate of 10 mm min^{-1} until failure (between 60 and 90 s).

Internal bond strength (IB) was measured according to EN 319 on ten specimens with dimensions 50×50 mm^2 and load was applied perpendicular to the plane of the panel. The specimens were glued to the aluminum blocks, and then the specimens were conditioned at a temperature of 20 °C and humidity of 65%. The conditioned blocks were attached to the IB test apparatus and the load was applied until failure (between 60 and 90 s).

3.4 Statistical analysis

The data were processed in STATISTICA 10 software (StatSoft Inc., USA) and evaluated using a one-factor analysis of variance (ANOVA), completed with Tukey's honest significance test (HSD test).

4 Results and discussion

4.1 Mass loss and weight percent gain

Mass loss is commonly considered as a main indicator of the degree and quality of thermal modification, and it is dependent on the wood species, temperature, time, and heating medium. For the studied specimens, M_L of spruce strands thermally modified at 180 °C was 2%. These results are in agreement with a previous study by Paul et al. (2007), who found mass loss of thermally modified Scots pine strands ranging from 0.5 to 2% at temperatures from 180 to 220 °C for 60 to 15 min, respectively.

The weight percent gain (WPG) shows the chemical uptake after acetylation. It depends on the wood species, temperature, time and the pressure of the process. The WPG of the aqueous solution was 136% after soaking the strands in the Ac_2O for 72 h. The result of WPG of the aqueous solution in the study reported by Dömény et al. (2015) was 66% for beech and 211.5% for poplar after pressure impregnation in Ac_2O at 20 °C and 0.8 MPa for 120 min. The WPG for dried spruce strands after 60 min of chemical reaction at 90 ± 2 °C was 3.9%, and after vacuum treatment was 3.6%. WPG of dry wood with different processes of acetylation

(pressure impregnation of Ac_2O or soaking with higher temperature 120 °C) on beech, poplar, and fir was 9.5–20% (Dömény et al. 2015; Pries et al. 2013; Papadopoulos and Traboulay 2002). WPG after vacuum treatment in the current research was much lower (about 62%) compared to the previous studies. This discrepancy could be due to different wood species, or the difference of treatment temperature, solution concentration, time, or pressure used in the acetylation process. Because the WPG in the current study is much lower, one expects less effectiveness of the acetylation treatment.

4.2 Density and moisture content

The density of the reference board and the other boards with modifications shows that there was no statistically significant difference (Table 1).

The EMC of strand board was 6.5% for the reference board and 5.9% for TM, which is a statistically significant difference (Table 1). TM_{SL} specimens do not have a statistically significant difference in EMC compared to control, which is understandable because there is still 76% of the untreated strands in the final board. These results correspond to results of previous studies, which showed that thermal treatment reduced the EMC of the strands. The study by Okino et al. (2007) showed a reduction in EMC for post-thermal-treated cypress OSB of about 0.7%. Other studies on pine OSB showed a decrease in EMC from 0.9 to 2.1% dependent on resin, time and temperature of thermal modification (Andrade et al. 2016; Paul et al. 2006; Mendes et al. 2013).

Table 1 Average values of density and equilibrium moisture content of boards at 20 °C and 65% RH

	Density (kg/m^3)		Equilibrium moisture content (%)	
Ref	596 (53)	A	6.5 (0.2)	D
TM	560 (29)	A	5.9 (0.2)	A, B
TM_{SL}	606 (55)	A	6.5 (0.2)	C, D
Acet	606 (74)	A	6.0 (0.2)	B
$Cork_{20\%}$	597 (50)	A	6.2 (0.2)	B, C
$Cork_{40\%}$	581 (50)	A	5.6 (0.5)	A

Means with the same letter in column do not differ statistically by the Tukey´s test ($\alpha = 0.05$). Numbers in parentheses represent standard deviation

The decrease of 0.5% in EMC between the reference and acetylated specimens was a statistically significant difference. Studies by different authors showed a greater effect of acetylation on EMC. EMC of particleboards made from acetylated Albizia particles was reduced from 9.4% EMC for reference boards bonded with isocyanate adhesive compared to 4.5% EMC of acetylated boards with 18% WPG (Imamura et al. 1989). The higher reduction in EMC in the study by Imamura et al. (1989) could be caused by higher WPG of acetic anhydride.

The EMC difference between reference (6.5%), $Cork_{20\%}$ (6.2%), and $Cork_{40\%}$ (5.6%) was statistically significant. The higher reduction in EMC in the boards made with cork particles corresponds to the amount of the cork particles (Table 1). Cork particles with slower water absorption and lower EMC than spruce cause reduction in final EMC of boards with cork particles.

4.3 Density profile

The shape of the density profile corresponds to a typical "U-shape" (Kelly 1977), with the higher density in surface layers and lower density in the core layer. Since there was only one density profile specimen per board, there was no statistical analysis performed in the current study. There is no apparent difference in the density profiles between the reference specimen and the specimens with modification in this research (Fig. 3). The density profile is highly dependent on the particle configuration and moisture distribution in the mat entering the press, as well as the rate of press

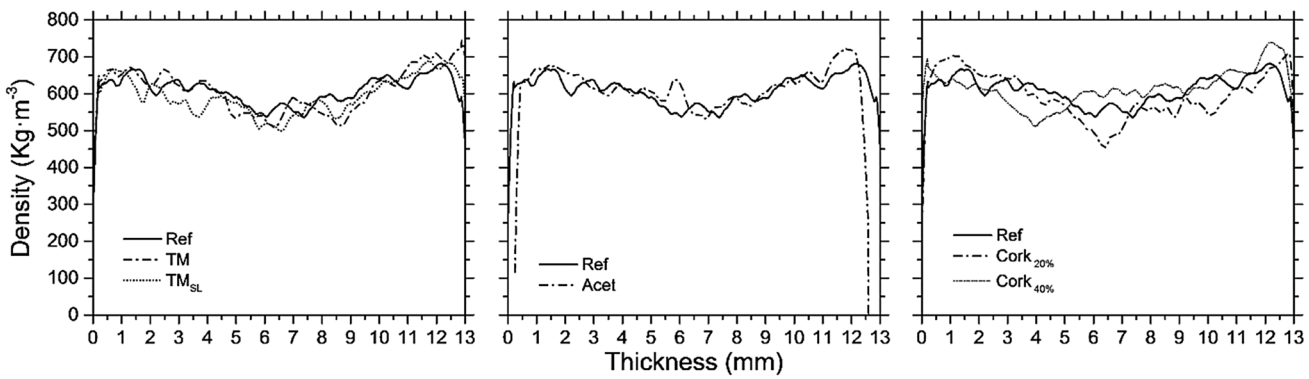

Fig. 3 Density profile of strand boards at 20 °C and 65% RH

closing, press temperature, reactivity of the resin, and the compressive strength of the wood particles. In the research by Youngquist et al. (1986), all control specimens showed slightly higher face densities and generally lower core densities than acetylated specimens. This trend was probably due to the acetylated flakes being less compressible and the fact that the acetylated flake mat entered the press at a much lower moisture content. Generally, no large density profile differences were noted among acetylated or control specimens, which is comparable with the research by Youngquist et al. (1986).

4.4 Water absorption

Water absorption at 99% relative humidity exposure for the reference board was 2.4%, for TM board 2.2%, and for TM_{SL} 2% after 2 h. Acetylated specimens and the specimens with cork had water absorption around 1.6% after 2 h. As shown in Fig. 4, there was a consistent difference in the water absorption from 24 h to 4 weeks. The water absorption after 24 h was, from highest to lowest, TM_{SL} (8.9%), reference (8.6%), TM (8.4%), $Cork_{20\%}$ (7.3%), Acetylation (7.2%) and $Cork_{40\%}$ (6.8%). After 1 week to 4 weeks of exposure, the specimens had a statistically significant difference between the reference board and the four treatments TM, Acet, $Cork_{20\%}$, and $Cork_{40\%}$. After 4 weeks of exposure at 99% RH, the water absorption was highest for TM_{SL} at 26.8%, followed by reference specimens at 26.3%, but there is not a statistically significant difference. Water absorption for TM was 25%, and for $Cork_{20\%}$ 23.6%. Water absorption for acetylated strand board was 22.2% and for $Cork_{40\%}$ 21.3%, but there was not a statistically significant difference between these two treatments.

Thermal treatment (TM specimens) reduced the WA because of the decrease in hydroxyl groups during modification. Small reduction in WA can be caused by thermal treatment at 180 °C, which is modification at a relatively lower temperature. It is expected to observe only slight improvements of the water adsorption with treatment at 180 °C, but also only a slight influence on the mechanical properties. Strand board made from 12% of TM strands by volume on each surface did not change WA. Acetylation and cork particles reduced WA significantly. Higher reduction in WA was observed when the amount of cork particles increased from 20% to 40% in the strand board.

4.5 Thickness swelling after soaking in water

There was a consistent rank order of the treatments based on thickness swelling after each soaking time (Fig. 5). However, the Tukey HSD test showed that there was no statistically significant difference between treatments in thickness swelling after 2 h soaking in water. Thickness swelling after soaking in water for 24 h was, from highest to lowest, TM (20.2%), reference (19.5%), TM_{SL} (17.4%), $Cork_{20\%}$ (15.5%), Acet (13.9%), and $Cork_{40\%}$ (10%).

There was no statistically significant difference between the reference and either of the thermal treatments. This result is similar to those from Mendes et al. (2013), where pine OSB made from 200 °C TM strands showed no difference, or greater TS than untreated OSB. Only a thermal treatment temperature of 240 °C resulted in a reduction in TS (Mendes et al. 2013). Other research on thermally modified OSB strands at 240 °C showed less TS in comparison to untreated OSB after 24 h-soaking (Paul et al. 2006). It seems that temperature of modification is a crucial factor for reduction in thickness swelling.

The reduction in TS of Acet specimens compared to reference strand board, after 24 h soaking, was about 5.6%, and after 1 week 6.9%. This result may be compared with reduction in swelling, in relation to untreated specimens, from 16 to 7% of acetylated Albizia particleboards with 18% WPG and bonded with isocyanate adhesive (Imamura et al. 1989). Youngquist et al. (1986) reported TS of boards made from acetylated aspen strands after 24 h soaking was reduced by 19% compared to untreated specimens. The thickness

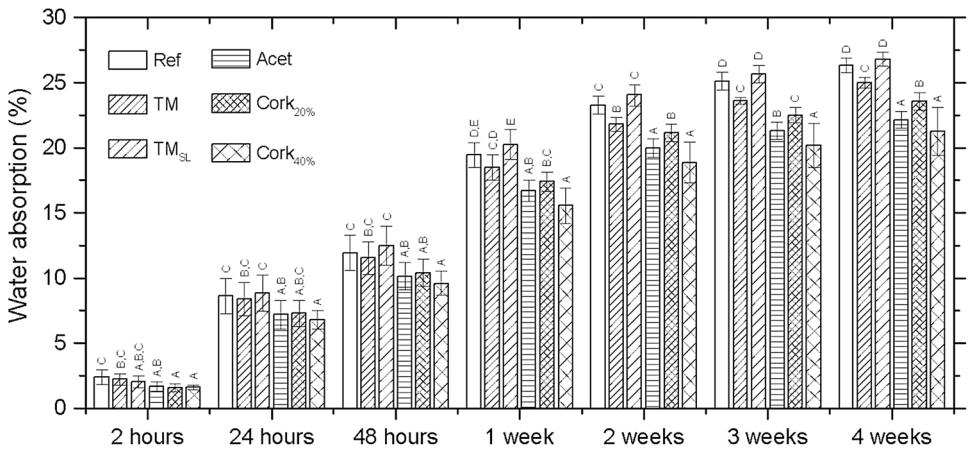

Fig. 4 Water absorption of tested specimens over time at 99% relative humidity exposure (columns with the same letter do not differ statistically by the Tukey's test $\alpha = 0.05$)

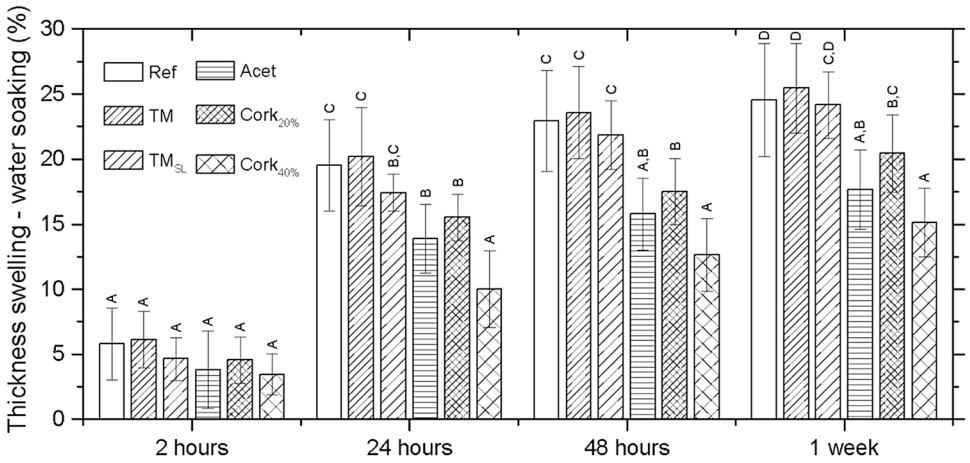

Fig. 5 Water-induced thickness swelling of tested specimens after varying duration of water immersion (columns with the same letter do not differ statistically by the Tukey's test $\alpha = 0.05$)

swelling after 2 h, 24 h and 1 week of OSB with acetylated fir strands was 2.5–6.5 times less for boards with 30 and 60 min (11% and 20% WPG) reaction time at 120 °C (Papadopoulos and Traboulay 2002). The current study had WPG of Ac_2O of less than 4%, which likely limited resistance to thickness swelling compared to the previous reports.

There was a statistically significant difference between the reference, $Cork_{20\%}$ and $Cork_{40\%}$ specimens after soaking times of 24 h, 48 h, and 1 week. Adding more cork particles to strand boards significantly reduced thickness swelling. Reduction in TS by cork particles can be caused by the material properties of cork—lower absorption of water compared to wood, and at the same time smaller cork particles filling the voids in the strand board and blocking the path for water into the panel.

4.6 Thickness swelling in 99% humidity conditions

From 48 h to 4 weeks of exposure to 99% humidity, the rank order of the treatment was consistent. There was no statistically significant difference in thickness swelling at 99% humidity after 2 h, where all TS values were less than 1%. The thickness swelling after 24 h was from the highest to lowest TM_{SL} (4.5%), TM (4.4%), reference (4.3%), $Cork_{20\%}$ (3.1%), $Cork_{40\%}$ (2.5%), and Acet (2.5%) (Fig. 6). For exposure of 48 h, the Tukey HSD test divided the specimens into two groups. First group was Ref, TM, and TM_{SL}, and the second group was Acet, $Cork_{20\%}$, and $Cork_{40\%}$. The first group has significantly greater TS than the second group. For exposures from 2 weeks to 4 weeks the results are in three statistically different groups. In the order of decreasing TS, the first group is Ref, TM, and TM_{SL}; second group is $Cork_{20\%}$, and third group is Acet and $Cork_{40\%}$. The average values of thickness swelling after 4 weeks of exposure were TM (26.5%), Ref (25.7%), TM_{SL} (24.4%), $Cork_{20\%}$ (20.8%), Acet (16.7%), and $Cork_{40\%}$ (15.4%). The rank order trend was the same for thickness swelling after soaking in water and thickness swelling at 99% relative humidity. Thickness swelling after soaking is faster and after one week showed the same trend as thickness swelling at 99% relative humidity after 4 weeks. This is connected to the slower absorption of water from the environment.

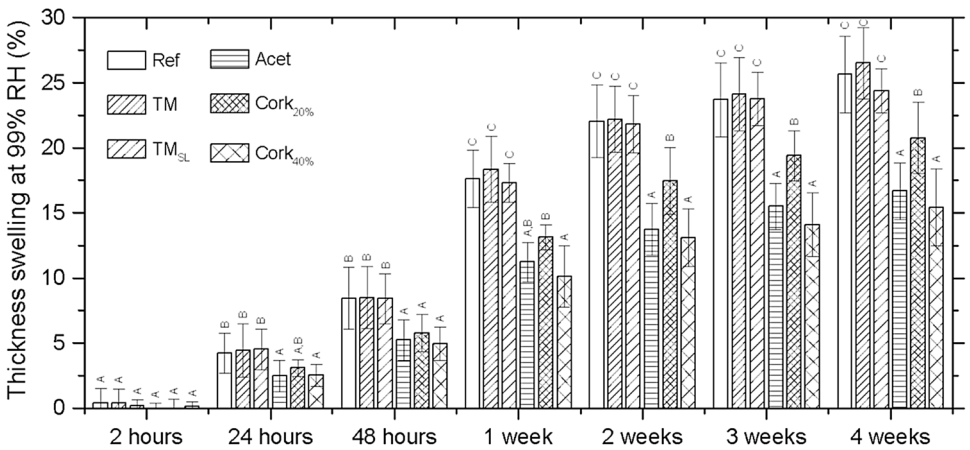

Fig. 6 Moisture-induced thickness swelling of tested specimens after varying duration at 99% relative humidity exposure (columns with the same letter do not differ statistically by the Tukey's test $\alpha = 0.05$)

Table 2 Average values of MOR and MOE of bending properties of strand boards

	MOR (N/mm^2)		MOE (N/mm^2)	
Ref	21.9 (8.1)	A, B	3677 (1071)	B, C
TM	8.4 (4.2)	C	1802 (709)	A
TM_{SL}	22.1 (9.5)	A, B	3867 (1496)	B, C
Acet	28.0 (9.4)	B	4498 (978)	C
$Cork_{20\%}$	21.2 (9.2)	A, B	2895 (1342)	A, B
$Cork_{40\%}$	14.4 (3.6)	A, C	1923 (609)	A

Means with the same letter do not differ statistically by the Tukey's test ($\alpha = 0.05$). Numbers in parentheses represent standard deviation

4.7 Bending properties

Thermal modification of all the strands (TM) in strand board significantly decreased MOR and MOE compared to the reference specimens (62% and 51%, Table 2). Thermal modification of only the surface strands (TM_{SL}) had no statistically significant effect on neither MOR nor MOE. Mendes et al. (2013) reported MOR and MOE of OSB made from TM pine decreased by 47% and 34%. A reduction in the bending properties was shown in other studies (Paul et al. 2006; Direske et al. 2018). This trend is also consistent with the results of Andrade et al. (2016), where increasing of the TM particles to the production of particleboard decreased the MOR and MOE. The reduction in the bending properties from control board to 100% TM was about 51% for MOR and 27% for MOE (Andrade et al. 2016). Increase in the brittleness of wood after thermal modification can cause a decrease in bonding properties of the board with 100% of thermally treated strands.

The Tukey HSD test showed that MOR and MOE of the reference board and the acetylated board were not statistically different. Youngquist et al. (1986) reported that boards made from acetylated aspen strands had MOE and MOR of 3820 MPa and 19.4 MPa, respectively, while reference boards had higher MOE and MOR of 4275 MPa and 29.3 MPa, respectively. The authors suspected there was poor wetting of the acetylated strands by the aqueous phenol–formaldehyde resin, and the presence of more voids in treated boards contributed to lower MOE and MOR (Youngquist et al. 1986). Poor wetting by the aqueous adhesives can cause decrease in the bending properties, however, wetting and curing of pMDI resin is different. There is still not enough research concerning the interaction of pMDI resin with acetylated wood.

The use of cork particles in strand board, with 20% of volume, did not change the bending properties. However, there was a reduction of 34% in MOR and 48% in MOE for $Cork_{40\%}$ compared to the reference board. Cork particles used in strand board reduce the bending properties, in general, because of the inferior mechanical properties of cork. While adding cork particles improved strand board resistance to water, this benefit must be balanced against the detrimental effect on mechanical properties. In this regard, more research is needed to find the optimum addition level of cork particles.

4.8 Internal bond

The internal bond strength was significantly lower for TM (0.11 MPa) compared to the reference specimens (0.38 MPa) (Fig. 7). However, there was no significant difference between TM_{SL} (0.33 MPa) and the reference specimens. This was caused by the composition of the TM_{SL} board, which had a core layer made from untreated strands and surface layers made from thermally treated strands. The IB test caused failure in the core layer, which is typical for OSB, because core density is characteristically low (Fig. 3). These results are similar to the results of Andrade et al. (2016) for thermally modified particleboards (TM 0.37 MPa, reference 0.89 MPa, 25% TM 0.52 MPa). Thermal modification of OSB strands caused a reduction in IB in other research studies (Direske et al. 2018; Mendes et al. 2013; Paul et al. 2006). Šernek et al. (2004) reported that TM of wood greater than 180 °C can reduce the potential for adhesive bonding, due to, in part, the movement of extractives to the wood surface, causing partial surface inactivation, which is detrimental for the wood adhesive interaction. Inactivation of the surface after thermal treatment can cause the reduction in internal bond strength of strand boards made with TM strands in the core.

There was a statistically significant difference between IB for acetylated (0.93 MPa) and reference (0.38 MPa) specimens. Acetylated board had the highest internal bond strength among all of the treatments. Other studies of acetylated OSB reported a reduction in IB due to acetylation (Abdolzadeh et al. 2011; Frihart et al. 2017; Papadopoulos

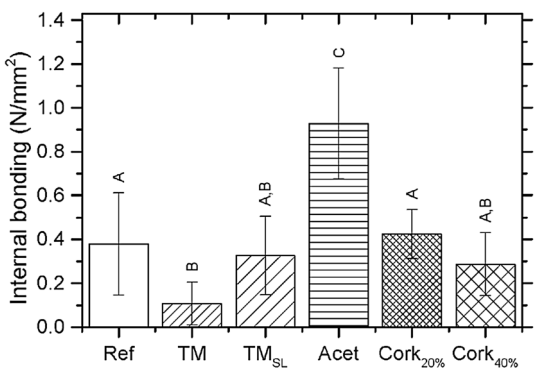

Fig. 7 Internal bond strength of strand boards (columns with the same letter do not differ statistically by the Tukey's test $\alpha = 0.05$)

and Traboulay 2002; Youngquist et al. 1986; Papadopoulos et al. 2006). However, those studies included different wood species, greater degree of acetylation, and most of the studies used phenol formaldehyde resin for board production. Phenol formaldehyde resin is an aqueous adhesive system, which relies on swelling a wood surface for penetration of the resin. The phenol formaldehyde molecule is polar, which is compatible with the polar hydroxyl groups in the wood cell wall. Acetylation reduces adsorption of the water component of phenol formaldehyde resin, which can cause lower bonding ability to the acetylated strands. Polymeric MDI resin, when used as an OSB adhesive, is a nonaqueous, nonpolar oligomer, which can easily penetrate wood surfaces. The presence of hydroxyl groups likely has little effect on pMDI penetration into wood. However, bound water molecules that are attached to the hydroxyl sites are available to form urea and biuret linkages with pMDI to advance the polymerization of the resin (Bao et al. 2003; Frihart et al. 2017). Due to its small molecular weight, pMDI molecules are able to penetrate into the amorphous regions of the wood cell walls. The change of hydroxyl to acetyl groups in wood after acetylation reduces the amount of water for polymerization with pMDI. However, the degree of acetylation in the current experiment was low (WPG less than 4%), therefore, there was sufficient bound water available for reaction with pMDI. The superior IB for the acetylated boards in this study cannot be explained.

There was no statistically significant difference in IB for strand boards made with $Cork_{20\%}$ (0.42 MPa), $Cork_{40\%}$ (0.29 MPa), or reference board (0.38 MPa). There was too much variability in the IB data to detect small differences between board types. The cork particles were small and granular, so they tended to fall to the bottom of the mat during the forming process. This would leave fewer cork particles in the core layer, and thus less effect on IB performance.

5 Conclusion

The modification of strands by acetylation or thermal modification changes the strand board properties. However, the change in mechanical properties and water resistance by these methods is a trade-off. Improved water resistance in some modified boards was linked to reduced bending properties or lower IB strength. Replacement of strands by cork particles improved water resistance but reduced bending properties.

EMC was reduced for boards containing thermally modified strands, acetylated strands, and boards containing cork particles. Water absorption of strand boards decreased only for acetylated boards and boards containing cork. Thickness swelling after soaking in water, and exposure at 99% RH, showed the same trends. Increasing the content of cork from 20 to 40% further reduced EMC and thickness swelling. Bending properties and IB decreased due to thermal modification and addition of cork at the 40% level. Acetylation caused an increase in MOR, MOE and IB in comparison to reference boards.

The use of pMDI in this study is beneficial in comparison to previous studies where aqueous adhesive systems were used. In addition, the degree of acetylation in this study was low compared to previous studies, which likely explains why some results of this study do not agree with previously published results. Results in this study show that it is still possible to improve strand board properties using acetylation or replacement with cork particles. More detailed research is needed to overcome variability and find optimized processes.

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