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Development of hemp hurd particleboards from formaldehyde-free resins

P. Alao[1,*], M. Tobias[1], H. Kallakas[1], T. Poltimäe[1], J. Kers[1] and D. Goljandin[2]

[1]Laboratory of Wood Technology, Department of Material and Environmental Technology, Ehitajate tee 5, EE19086 Tallinn, Estonia
[2]Department of Mechanical and Industrial Engineering, Tallinn University of Technology, Ehitajate tee 5, EE19086 Tallinn, Estonia
[*]Correspondence: percy.alao@taltech.ee

Abstract. Low density of hemp hurd (Cannabis Sativa L), better end of life impact, performance comparable to wood chips and low energy requirement for cultivation make it a suitable alternative raw material for particleboards (Pb). However, due to concerns about sustainability and formaldehyde emissions, it is essential to develop the new bio-based resins from renewable resources. In this research, the mechanical and physical properties of Pb produced from hemp hurds (HH) and a variety of resins: Urea-formaldehyde (UF), formaldehyde-free acrylic resin (Acrodur®) and bio-based soy resin (Soyad™) were compared to those of wood particles (WP) bonded with UF. The results indicate that boards from HH are generally lighter than WP with a 5.6% variation between HH+UF and WP+UF. Hemp boards based on soy-resin showed higher tensile performance, with an average of 0.43 MPa compared to the 0.28 MPa and 0.24 MPa of (HH+UF) and (WP+UF) respectively. Nevertheless, thickness swelling (TS) of HH+UF (27%) was the least, while there was no significant difference in the water absorption (WA) compared to HH+Soyad4740, both were still lower than that of WP+UF. The overall outcome shows that bio-based soy resin can be a suitable alternative to UF as a binder in Pb production.

Key words: bio-resin, hemp hurd, mechanical properties, particleboard, urea-formaldehyde.

INTRODUCTION

In the 21st century, maintaining sustainability in resources and the environment is the main challenge. The rapid increase in growth and imbalance between consumption and limited resources are of essential concern (S. Islam & Bhat, 2019). Therefore, a major trend is to develop new materials and solutions (Latif et al., 2015). One of such directions is related to particleboards from wood. However, this has caused a shortage of wood supply, increased deforestation and over-harvesting, especially in most developing countries (Mirski et al., 2017). As a result, it is more desirable to use non-traditional forest resources like hemp, flax and sisal since they offer comparable performance (Khazaeian et al., 2015). This will further enhance cleaner production, reduction in the consumption or over dependence on a raw material and positive climatic impact (Muizniece, Vilcane & Blumberga, 2015).

Cannabis Sativa L. is one of human's earliest cultivated industrial crops (Tobias, 2019). It requires low input for cultivation, it is easily diversified and requires no fertilizer or herbicides; moreover, it is environmentally friendly (Liu et al., 2017). Additionally, it is one of the strongest and stiffest natural woody materials, with its structure consisting of crystalline cellulose (55–72 wt. %), hemicellulose (8–19 wt. %), lignin (2–5 wt. %), waxes, and oils (Islam et al., 2010). Hemp is obtained by planting the hemp seed. When cultivated, CO_2 is trapped from the atmosphere causing a reduction in global warming and increasing air purification (Green Building, 2018). There is no particular soil preference for cultivation and the plant has a fast growth rate, reaching a height of about 4 m in just 100 days (Insulation-info.co.uk, 2019). Europe, China and Canada are the biggest producers of hemp. Natural fibres from hemp are being used to substitute conventional materials and synthetic fibres like glass in thermal insulation and as reinforcement for composites (Lühr, Pecenka & Gusovius, 2015).

For the production of wooden structural elements, such as trusses, plywood, particleboards, fibreboards and furniture, synthetic adhesives based on urea-formaldehyde, polyurethane, polyvinyl acetate, polyester and epoxides are commonly used because they provide excellent adhesive properties, high rigidity, and dimensional stability. However, wastewater from the production of these resins are found to contain a high amount of compounds that are toxic to aquatic life (Łebkowska et al., 2017). Furthermore, there are concerns about human and animal health due to the emission of volatile organic compounds (VOCs) from formaldehyde that is carcinogenic when inhaled and causes asthma, irritation of the eyes, nose, and respiration during hot pressing. Other problem stems from the fact that most synthetic adhesives are obtained from the production of hydrocarbons, which considerably affects air and environmental pollution (Alao et al., 2019). These and many more have led to a surge in research towards deriving appropriate substitutes (M.S. Islam & Miao, 2014).

Bio-based sustainable alternatives studied as potential substitutes are from natural materials like oilseeds and soybean. They are cheap, renewable, and biodegradable and applied in the past to substitute petroleum-based products (Hamarneh, 2010). Tannings, lignin, carbohydrates, and unsaturated oils are the other resins considered as possible replacements. Lately, commercial manufacturing companies have shown increasing interest in developing formaldehyde-free/bio-based adhesives for particleboards and other similar panel products. As an example, M. S. Islam & Miao (2014) focusing on the optimization of the processing conditions of flax fabric used Acrodur that is a product of BASF. It is an aqueous formaldehyde-free resin obtained by the dispersion of the polyester of polycarboxylic acid and polyalcohol in water. According to their results, the resin has the specific tensile strength of 57.9 MPa-cm^3g^{-1} and Young's modulus of 5.5 GPa-cmg^{-1}. In the automotive industry, wooden and natural fibre products for cars have been moulded using this adhesive.

The purpose of this research is to develop particleboards from hemp hurd and to ascertain the feasibility of using formaldehyde-free resins as alternatives to urea-formaldehyde. The objectives are: to substitute UF with Acrodur® /Soyad™ resins for hemp hurd particleboards; to investigate the mechanical properties, physical properties and air permeability; to compare and analyse the properties with wood particleboards bonded with conventional resin (UF).

MATERIALS AND METHODS

Hemp hurd (HH) and wood particle (WP) board

Hempson OÜ supplied hemp hurd (HH) and we obtained wood particles from AS Repo Vabrikud. The particleboards were made using the same process, but, for the hemp Pb, the HH was first manually cleaned. The board target density of 600 kg m^{-3} was chosen for this research (based on EN 314-4 for boards of thickness 13–20 mm) and the dimension was 400×400 mm. The Pb was produced from single-layer 1,200 g of hemp hurd/wood chips (7% average moisture content (MC)) and resin (11% wt. of the hemp hurd or wood particles dry matter), see Eq. (1) for the MC calculation. The adhesives were Urea-formaldehyde (UF), formaldehyde-free acrylic resin (Acrodur® 3510 and 3558 from BASF) and bio-based soy resin (Soyad™ CA4740EU and CA1025). The mixture was stirred in a labor mixer for 3 min, following slow application of the resins to the hemp hurds/wood chips then formed in a frame with a thickness of 15 mm. The blends were hot-pressed at a temperature of 140 °C and pressure of 2 MPa for 5 min. Table 1 shows the properties of the resins, while Fig. 1 shows a schematic of the process of board production.

$$\mathrm{MC} = \frac{w_2 - w_3}{w_2 - w_1} \times 100\% \quad (1)$$

where w_1 – weight of container with a lid; w_2 – weight of container with a lid and sample before drying; and w_3 – weight of container with a lid and sample after drying.

Table 1. Properties of the adhesives used (Tobias, 2019)

Description	Synthetic resin	Formaldehyde free acrylic resin: Acrodur®		Bio-based (Cationic) resin; Soyad™	
	Casco UF	3510	3558	CA1025	CA4740EU
Colour/Physical state	white-hazy liquid	yellowish liquid	yellowish liquid	golden, liquid	golden, liquid
Solid content (%)	61	50	50	25	48
pH value	7.2–8.4	3–4	3–4	2.8	3.5
Density (gcm^{-3})	1.27–1.30	1.2	1.2	1.07	1.13
Viscosity (mPa.s @23 °C)	100–340	150–300	300–1,500	175	175
Density (g cm^{-3})	1.3	1.2	1.2	1.07	1.13
For board production					
Adhesive (wt.% of hemp mass)	11	11	11	11	11
resin (wt.% of solid content)	61	50	50	23	48
Hardener (g)	40.25	–	–	58.89	51.69
Amount of water required	–	–	–	56.80	–

Determination of board density

The density of the specimens was determined based on EVS-EN 323. The specimens were cut to test sizes of 50×50 mm, weighed using the Mettler Toledo B2002-S balance (d = 0.01 g, max weight = 2,100 g) and measured with a digital calliper (d = 0.01 mm). The width, length and thickness of the specimens were measured at three points to the nearest 0.5 mm. We rounded up the average measurements to the nearest 1 mm. The density in kg m^{-3} was calculated from the weighed mass and volume.

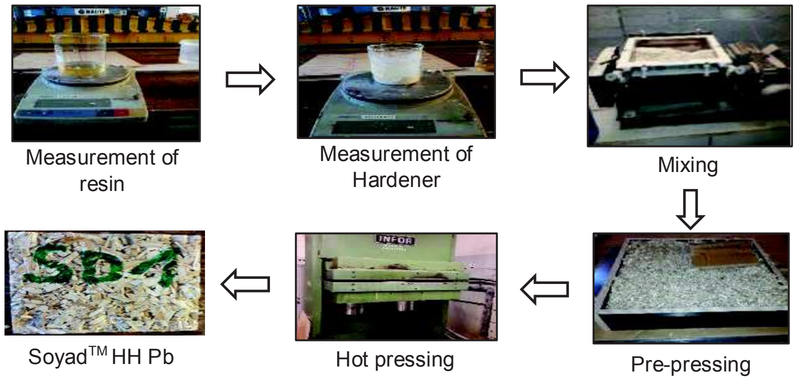

Figure 1. The particleboard production process (Tobias, 2019).

Mechanical tests

The resistance to tension perpendicular to the surface of the test specimen (50×50 mm) was determined by applying the tensile force until the rupture occurs in accordance with EVS-EN 319. The bending strength was evaluated according to EVS-EN 310 by placing a load on the centre of the test specimen (50×250 mm) supported at two points. We used EVS-EN 320 to investigate axial withdrawal of screws by measuring the force required to withdraw a defined screw from the test piece (65×50 mm). All these tests were performed at room temperature (23 °C) using the Instron 5866 machine.

Water absorption and thickness swelling

The thickness swelling and water absorption were determined by immersing the specimens (50×50 mm) in water at 20 ± 2 °C and relative humidity of 65 ± 5% for 24 hr according to EVS-EN 317. After the test, the specimens were drained, weighed and re-measured. The percentage change in mass (water absorption (WA)) and dimension (thickness swelling (TS)) were calculated using the following equations:

$$\mathrm{WA} = \frac{m2 - m1}{m1} \times 100\%, \tag{2}$$

where m_1 is the mass of the test specimen, in grams (g), after initial drying and before immersion; m_2 is the mass of the test specimen, in grams (g), after immersion.

$$TS = \frac{t_2 - t_1}{t_1} \times 100\% \tag{3}$$

where t_1 is the average thickness of the test specimen (mm), after initial drying and before immersion; t_2 is the average thickness of the test specimen (mm) after immersion.

Air permeability test

A fabricated test apparatus was used to expose the test specimens (100×100 mm) to two stages of predefined pressure, see Fig. 2. The test was performed to evaluate the insulation properties of the boards by determining the airflow resistivity following EVS-EN12114. The samples were sealed at the edges with tesa tape to prevent air passage during the test. The pressures in the second stage were calculated using the equation below.

$$\Delta p_i = 10^i \frac{\log \Delta p_{max} - \log\Delta p_{min}}{N} + \log\Delta p_{min} \quad (4)$$

where Δp – pressure difference, Pa; N – total number of pressure steps; and i – number of pressure steps.

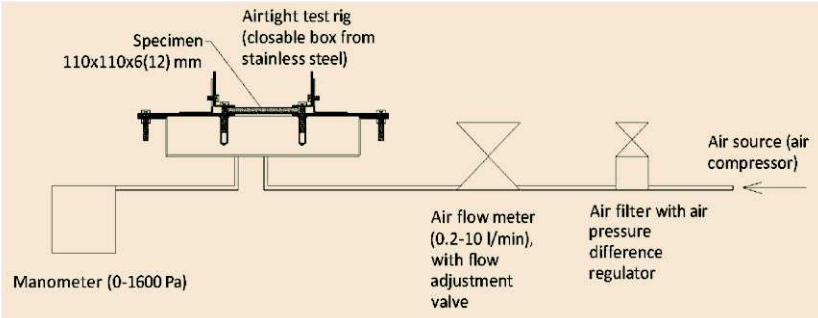

Figure 2. Set–up of air permeability test equipment. Source: (Kukk et al., 2017).

Fig. 3 shows the test specimen placed in the airtight test rig and held in place using metal screws. The pressure was applied from a small pipe at the bottom of the box. The maximum pressure difference (Δ_{pmax}) was 550 Pa while the minimum (Δ_{pmin}) was 50 Pa. In the first stage, three pulses of Δ_{pmax} were used for about 2 min. The specimens that were airtight at that stage were not subjected to further testing. For specimens with continued airflow, Δ_{pi} was applied until the estimated minimum pressure.

Below (Fig. 4) presents the cutting layout for all the test pieces. Six (6) Pb variants were produced based on the resins and particle material.

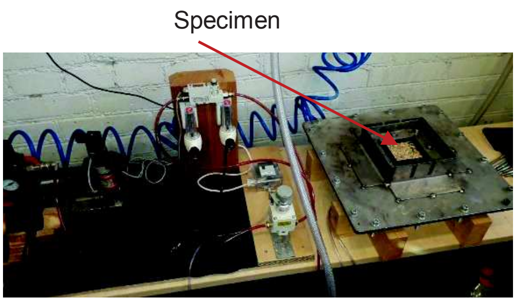

Figure 3. Air resistivity testing of a specimen under the apparatus.

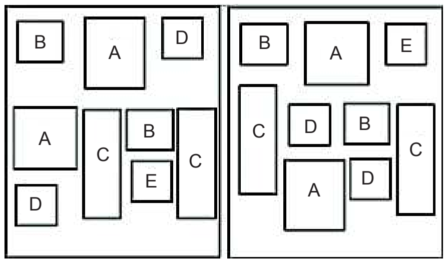

Figure 4. Cut plan for the air permeability (A), axial withdrawal of screw (B), bending (C) tensile strength (D) and density/thickness swelling/water absorption (E) (Tobias, 2019).

RESULTS AND DISCUSSION

Density

Fig. 5 reveals the average density results of all the boards. The values ranged from 477 kg m^{-3} (HH+ Soyad™ CA1025) to 581 kg m^{-3} (WP+UF) with the 5.6% difference between HH+UF and WP+UF linked to low density and the porous structure of hemp (Kallakas et al., 2018). A comparison of HH boards shows that the properties of the adhesives also influence the finite Pb density. For instance, according to Table 1, Soyad

CA1025 has a low solid content (25%) and requires water in preparation, some of which evaporates, causing a decrease in the final density. The 9.3% increase by HH+Soyad CA4740EU confirms this. Interestingly, there was a decrease of 6.8% by HH+Acrodur compared to HH + Soyad CA4740EU, which may be because Acrodur® is a water-based acrylic binder that already, exists in the liquid form. However, its value was still slightly higher than that of HH+Soyad CA1025. The variation of 1% between HH+Acrodur may be due to the processing inconsistency from the laboratory scale process, which is also noted in previous research. Therefore, it was impossible to achieve the target density of 600 kg m^{-3} for all the boards (Valarelli et al., 2014).

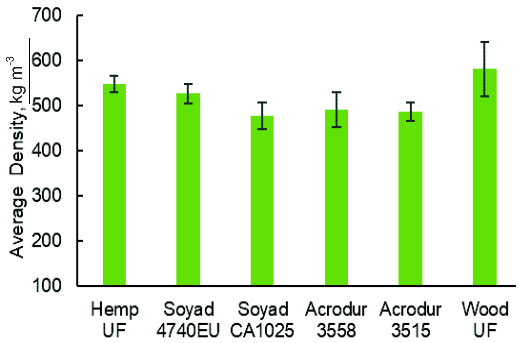

Figure 5. Average density values of test specimens.

Tensile strength

Fig. 6 shows the results of average tensile strengths. Despite the low density of the soy-based hemp Pb, their tensile performance was the highest, 0.43 ± 0.07 MPa (Soyad CA1025) and 0.44 ± 0.1 MPa (Soyad 4740), there was no significant difference. But, there was an increase of approximately 17% in strength for the HH+UF in comparison to WP+UF, which suggest strong interfacial interaction between the hemp hurds and the resin, and improved adhesion (Kallakas et al., 2018); (Kallakas et al., 2019). Overall, HH+Acrodur 3558 had the lowest value (0.22 ± 0.04 MPa) that may be because of the high viscosity (300–1,500 MPa.s) of the resin that prevents proper flow and filling of the cavities in the hemp particles. EN 312 stipulates the minimum standard value for tensile strength perpendicular to the plane of the particleboards as 0.24 MPa and from the obtained results, only HH+Acrodur 3558 did not meet this standard.

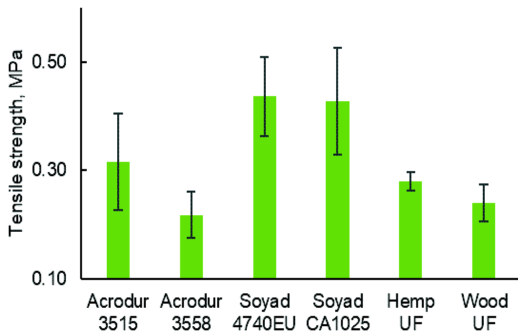

Figure 6. Tensile strength perpendicular to the plane of the boards.

Bending strength

Fig. 7. presents the bending properties of all the test specimens. HH+Soyad CA4740 has the best result in bending (13.9 MPa), which corresponds to a 12% and 78% increase compared to HH+Soyad CA1025 (12 ± 2 MPa) and HH+UF (3 ± 0.4 MPa) respectively. All the HH Pb performed better than the WP+UF. Furthermore, the comparison of the hemp boards shows that soy-resin hemp Pb demonstrated better modulus of elasticity (MOE), which could be due to the increase in compactness of the

board, caused by the good interfacial interaction between the resin and the hemp hurds (Akinyemi et al., 2019). However, WP+UF showed the best MOE (650 ± 100 MPa) due to the high density of the board, see Fig. 8. General-purpose boards for use in dry conditions are required to have a maximum bending strength of 11.5 MPa according to EN312, but only the soy-based hemp boards meet this standard.

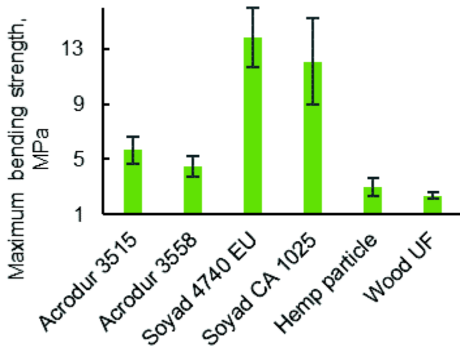

Figure 7. Bending strength of the boards.

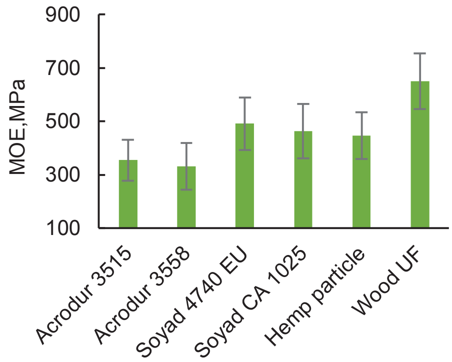

Figure 8. Modulus of elasticity of the boards.

Resistance to axial withdrawal of screws

Ten specimens were tested for the resistance to axial withdrawal of screws. Fig. 9 presents the average results. The Hemp-based boards generally showed better properties than the wood particleboard. The highest axial screw withdrawal strength, 21.6 ± 2.7 N mm^{-1} was obtained for the HH+Soyad 4740 at 45.8%, exceeding UF bonded HH and WP. A similar performance of 11.7 N mm^{-1} was obtained for UF bonded HH and WP boards. However, if a strong bond exist between the WP and adhesive, the high density of wood compared to hemp should always enhance resistance against the withdrawal of screws, because of the added stiffness of the board (Joščák et al., 2014). Although insignificant, the low margin of correction (0.3 N mm^{-1}) of WP+UF in comparison to HH+UF (1.9 N mm^{-1}), may be considered as a partial confirmation here. However, none of the particleboards meets the stipulated standard given by EN 622-4.

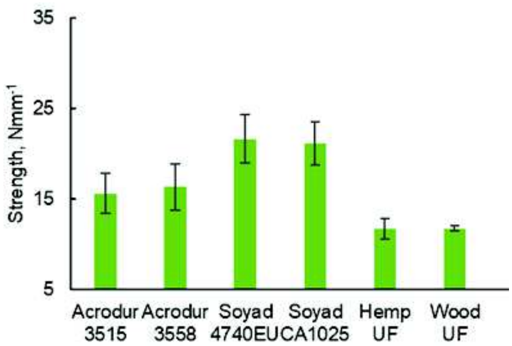

Figure 9. Resistance to axial withdrawal of screws.

Water absorption and thickness swelling

All the test specimens gained mass and showed dimensional changes after the 24-hour immersion, see Fig. 10. The best TS (27 ± 8%) corresponding to WA of (128 ± 9%)

was by HH+UF. This is an improvement of 40% and 14% in comparison to UF bonded WP respectively, even though HH general have high porosity than WP. The results show that the interaction of the resin with the HH is a more important determinant of dimensional stability and moisture resistance than the porosity or density of the final board. The soy-resin hemp boards also produced better results than WP+UF, however, Acrodur bonded hemp boards had the most affinity for moisture because the WA and TS outcomes were higher than the other samples. Considering our experimental procedure (EVS-EN 317), there is no standard maximum value given by EN 312 for particleboards WA, but the TS values for non-load bearing boards for use in dry and humid conditions are 15% & 14% respectively. None of the boards from this study achieved the required standard. This outcome may not be surprising, giving that there was no prior modification of the particles or coating of the finished boards with water repellent chemical. Earlier research observed that the board-density influences the TS and WA. (Akinyemi et al., 2019). Yet, this effect is not clear in this study because the high-density WP+UF gives a better result compared to the low-density HH+Acrodur, but different outcome to HH bonded UF and Soyad™.

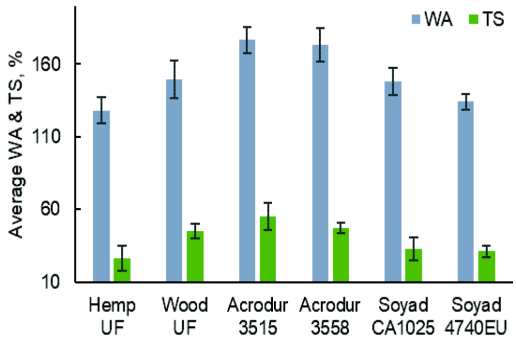

Figure 10. Water absorption and thickness swelling of all boards after 24-hour immersion.

Air permeability

The HH boards were all airtight at the first stage pressure (550 MPa); hence, the results presented in Table 2 only show the outcome for the WP with an average value of 1.84 L s^{-1} m^2.

Although research on this topic is insufficient, the outcome is comparable to (Kallakas et al., 2018) where 1.73 L s^{-1} m^2 was reported. This result confirms that the interaction between the resins and hemp hurds is stronger than that between the wood particle and the UF resin.

Table 2. Air permeability of the wood particleboard

Pressure steps	Pressure, Pa	Average Air permeability, L min^{-1}	Air flow, L s^{-1} m^2
2nd	50	0.29	0.48
	73	0.41	0.67
	108	0.56	0.98
	158	0.82	1.40
	232	1.12	2.03
	341	1.66	2.77
	500	2.45	4.08
1st	550	2.67	4.13

CONCLUSIONS

This study examined the possibility to use formaldehyde-free resin with hemp hurds to produce particleboards. The use of hemp hurds bonded with bio-based resin resulted in enhanced mechanical properties of the particleboard. However, the poor outcome in the TS and WA shows that prior modification of the hemp particles or the use of water repellent additives should be considered for wet application. Although the airtightness was excellent, evaluations on a larger scale, vis-à-vis conventional insulation materials, are needed. Finally, it is required to compare the performance of the wood particleboards, especially for better justification**,** those bonded with soy-based resins with the HH particleboard.

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