

## An impact of surface spray and pressing temperature on the properties of high density fibreboards

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**Abstract:** *An impact of surface spray and pressing temperature on the properties of high density fibreboards.* The objective of this study was to investigate the effects of chosen process parameters: water spray amount and 3<sup>rd</sup> press heating section temperature on the mechanical, physical properties of ultrathin (2.5 mm) industrial high-density fibreboards (HDF) produced with 5% of recovered HDF (rHDF) addition. Boards were produced with 0 ml/m<sup>2</sup> – V0, 8 ml/m<sup>2</sup> – V8, 16 ml/m<sup>2</sup> – V16 and 32 ml/m<sup>2</sup> – V32 of surface water spray addition on top and bottom side in industrial hot continuous press with 3<sup>rd</sup> heating section temperature setups: 145°C (V45), 160°C (V60) and 175°C (V75). After variants examination with different surface water spray amount it was found, that there is roughly linear positive correlation for MOR increase for up to 10% comparing V0 to V32 and for surface roughness decrease for up to 31%. Surface water spray improved IB for up to 21% while WA decreased for up to 9% for V8 comparing to HDF produced without surface water spray addition. According to 3<sup>rd</sup> press heating section temperature influence – MOR and MOE has increased while other mechanical properties worsen with pressing temperature increase – drop in IB and SS.

*Keywords:* wood-based panel, HDF, recovered fibre; water spray, pressing temperature.

### INTRODUCTION

The production volume of medium density fibreboards (MDF) in Europe is constantly increasing (“Food and Agriculture Organization. Forestry Production and Trade” 2020). One of the reasons for that is the possibility of wide usage and finishing of those products (Nicewicz, Sala 2014). As the production output is growing, more raw wood material is needed, which results in price increases ([www.drewno.pl](http://www.drewno.pl)).

Round wood for MDF production such as pine spruce and less popular species (alder, birch or beech) may be substituted by recovered wood, newsprint, plantation wood species, straws or post use wood-based panels (Oniško 2011). The usage of waste material for particleboard industry in UK has increased for over 25% from 2015 to 2018 and will further increase next years (Tolvik Consulting 2018). Although the use of recovered materials is eco-friendly and helps to reduce costs, reintroducing those materials is negatively influencing mechanical and physical properties (Hwang et al. 2005). That is why it is important to adjust production parameters to minimize this undesirable effect (Wan et al. 2014).

Most of the properties of wood-based panels (WBP) are created during the hot pressing process; that is why this operation has a major effect on the balance of properties of the resulting panel. Heat and mass transfer is crucial to achieve appropriate product quality and to minimize pressing time (Thoemen et al. 2010). One of the ways to improve heat transfer is to inject a quantity of steam into the bottom of the wooden mat material before entering the continuous press system, or use high frequency or microwave material preheating. All these methods have the advantages of reducing the press cycle time and the post-curing time, which can provide 15–30% production capacity increase. Additionally, it enables press section temperature reduction by faster heat transfer into the mat core, but there is also less pressure required at continuous press infeed, which prolongs chains and steel belts lifetime. From the customer point of view, thanks to above solutions, the board density profile

may be improved, in particular, with an increase in surface density, which, on the other hand, enables panels surface adaptation for finishing, providing e.g. glossy, more closed surface, suitable for lacquering (www.ialpal.com; Pereira et al. 2004; Deng et al. 2006). Despite many advantages of the above ways of wooden mat preheating, their basic disadvantage is an investment cost required, which is not neutral for to the final product price. One of the most important factors influencing heat transfer is moisture – starting with mat moisture content, which linearly affects the height of mat core temperature, which provides more optimal resin curing (Cai et al. 2006). A reverse influence of panel moisture content on mechanical properties can be observed. Together with panel moisture increase, the modulus of rupture (MOR), modulus of elasticity (MOE) and the internal bond (IB) are negatively affected, whereas thickness swelling (TS24) and water absorption (WA) properties are positively affected by the panel moisture (Bekhta, Niemi 2009). To improve heat transfer during WBP hot pressing process, it is possible to add additional water together with release agent solution on the surface of wooden material before the pressing. Based on the previously conducted experiments, increasing surface water spray amount from 0 ml/m<sup>2</sup> to 16 ml/m<sup>2</sup> per side (top and bottom) causes an increase in the mat core temperature during hot pressing of about 17%, while increasing the amount to 32 ml/m<sup>2</sup> causes an additional ~8% mat core temperature increase; this gives a total mat core temperature increase of about 25% (Sala 2020). Considering the fact that the release agent solution is commonly used for HDF production together with surface water spray, it does not significantly increase the total production costs.

Moreover, press parameters are crucial to the final MDF properties (Gul et al. 2017). A proper setup of pressing time, pressure and temperature enables heat transfer during hot pressing. The heat is first transferred by conduction from press heating sections to the mat surface and into the mat, and then, by convection (i.e. gas flow in combination with phase change) between gas and particles in the mat and the mat edges (Thoemen, Humphrey 2006; Winandy et al. 2004). Together with water coming from mat moisture content and/or additional water spray, these processes are crucial for mat preheating and resin curing (Sala 2020; Meyer, Thoemen 2007). The proper press parameters setup ensures the desired board performance. Although increasing pressure, time and temperature of hot pressing may positively influence the mechanical and physical properties of the board (Gul et al. 2017; Kargarfard, Latibari 2014), it may also lead to fibre degradation (Winandy, Krzysik 2007).

Two types of hot presses can be listed: Multi-Opening Press System (MOPS) and Conti Panel System (CPS). Although MOPS may be less popular, beyond doubt, it has a few advantages, such as: easy and multifunctional control with high shelves position accuracy thanks to advanced hydraulic control. What is more, high compression speeds result in good surface soundness board properties, while steam venting enables degassing of wider presses and results in obtaining the desirable board properties. Nowadays, MOPS are mainly used for oriented strand boards (OSB), oriented strand lumber (OSL), hardboards (HB) and softboards (SB) – insulation (Hassani et al. 2019; Jud et al. 2004; www.dieffenbacher.com). CPS is a continuous press and can be used for, e.g. MDF, particleboard (PB) production on wide range of widths, thicknesses and densities. Depending on the last two parameters, press length is designed to achieve proper press factor (pressing time per nominal panel thickness unit). One of the advantages of CPS solution is high speed temperature control system, enabling higher press temperature operation and higher productivity. Additionally, temperature changes are possible during production due to movable press frame concept (Fig. 1).

It is possible thanks to separate heating circuits for individual heating section. In example, high density fibreboard (HDF) press 1<sup>st</sup> press heating section is responsible for heat transferred from heating section through press rolling rods and press steel belt to the mat surface. In this section, pressing pressure and temperature is reaching maximum. 2<sup>nd</sup> press heating section is overheating surface and heat is transferred to the middle of fibrous mat.

Pressure in this section is slowly reduced while temperature may be around maximum. After reaching 3<sup>rd</sup> press heating section, the resin in the surface is already pre-cured and mat core is preheated to cure core resin. The pressure in this section may be reduced to minimum while temperature is also reduced by around 20–30%. In the 4<sup>th</sup> press heating section, the temperature is the lowest, while pressure is again increased to reach and keep assumed board thickness.

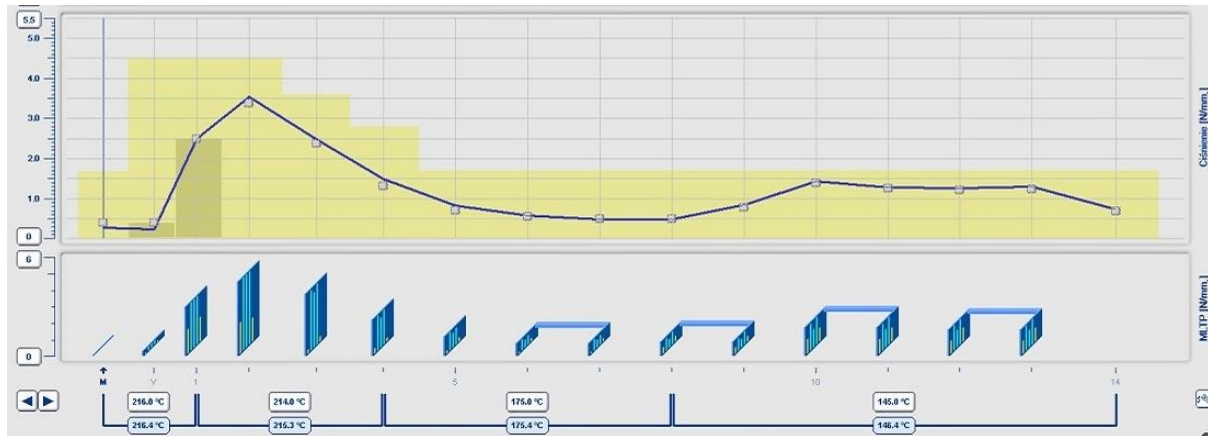


Figure 1 HDF pressing pressure with heating sections (production flow – from left to right) (photo C. M. Sala)

Considering the fact that the post used materials introduction into MDF production will be more popular and this requires process adaptation, the purpose of this investigation was to evaluate impact of water spray amount and 3<sup>rd</sup> press heating section temperature influence on selected mechanical and physical properties of high density fibreboards (HDF) produced with 5% of recovered HDF addition. Those impacts were chosen as the one that may be responsible for resin curing and final board properties.

## EXPERIMENTAL

The experiment was divided into 2 parts examining 1) water spray amount influence and 2) 3<sup>rd</sup> press heating section temperature influence on HDF properties, however, material and methods applied have several common parts.

## MATERIAL

HDF assumptions: thickness – 2.5 mm, density – 860 kg/m<sup>3</sup>, wood for production: Polish State Forests pine (*Pinus sylvestris* L.) with 5% addition of recovered high density fibreboards (rHDF), as cutoffs and production leftovers, formaldehyde emission – CARB 2 with the formaldehyde content <5.0 mg/100 g (EN 12460-5; IOS-MAT-0003). Chips were produced with Metso 10 knives disc chipper, fibres on industrial Metso defibrator EVO56 with following parameters: preheating pressure 0.94 MPa, preheating time: 3.2 min, an average defibrating energy consumption: ~145 kWh/t. These defibrator parameters resulted in fibre bulk density of 21.65±0.20 kg/m<sup>3</sup> dried to 10.5%+/-1.0% of moisture content. Chemical additives recipe: paraffin – 0.5% calculated with reference to the weight of the oven-dry fibres, glue – MUF (melamine-urea-formaldehyde) resin (melamine content 5.2%, molar ratio 0.89, solid content 66.5%) using the following recipe: 11.0% of dry resin weight referred to dry wood, urea 21.0%, hardener 3.0% (ammonium nitrate water solution), both calculated as dry content to dry glue weight ratios. For this investigation, four different amounts of surface water spray with 3% of TAG Chemicals Fiberline 402 ws 12 CAF release agent amount were used. On top and bottom side of the fibrous mat, the amount of water spray (hereinafter called

“spray”) was the same, depending on the mat variant, i.e.: V0 – 0 ml/m<sup>2</sup>, V8 – 8 ml/m<sup>2</sup>, V16 – 16 ml/m<sup>2</sup> (standard for other trials) and V32 – 32 ml/m<sup>2</sup>. An industrial Dieffenbacher continuous press system was used for HDF production – press length was 22.8 m, temperatures of hot pressing of 1<sup>st</sup>, 2<sup>nd</sup> and 4<sup>th</sup> heating section were constant, while 3<sup>rd</sup> heating section temperature varied depending on the variant: V45: 145°C, V60: 160°C (standard for other trials) and V75: 175°C.

## METHODS

The adjustment of rHDF material dosage is described in Sala et al. (2020) regarding cutoffs and trims addition similar to HDF mechanical and physical parameters, together with a density profile examination. HDF board moisture content in PART 2 was measured 30 minutes after pressing process according to EN 322 on 5 samples.

### *Statistical Analysis*

An analysis of variance (ANOVA) and t-tests calculations were used to test ( $\alpha = 0.05$ ) for significant differences between factors and levels, where appropriate, using IBM SPSS statistic base (IBM, SPSS20, Armonk, NY, USA). A comparison of the means was performed when the ANOVA indicated a significant difference by employing the Duncan test.

### *The amount of release agent surface water spray*

The surface water spray was dosed on top and bottom of fibrous mat surfaces by WEKO spray units with rotary spraying discs. The water solution of release agent was automatically prepared by WEKO devices due to the setup of 3% of release agent mixed with fresh water. The assumed proper dosage of water spray on fibrous mat surfaces, depending on the variant, was also realized automatically by WEKO spray units.

### *3<sup>rd</sup> press heating section temperature setup*

Depending on the variant, 3<sup>rd</sup> press heating section temperature was set on industrial PLC visualization as a set point controlled by Dieffenbacher software and an automatic thermal oil control valve. The remaining parameters of hot press were kept by the software on the assumed level.

### *Selected mechanical and physical parameters of the produced panels*

The selected mechanical and physical parameters were tested following the methodology described by Sala et al. (2020). The HDF board moisture content in PART 2 was measured 30 minutes after pressing process in accordance with EN 322 on 5 samples.

## RESULTS AND DISCUSSION

### **PART 1: The surface water spray amount**

#### *Mechanical and physical properties*

##### *Density profile*

Depending on various HDF density profile shape, i.e. surface layer density (SLD) and core density (CD), different final mechanical and physical panel properties can be achieved (Wong et al. 2000). In order to better understand the influence of the surface water spray amount on HDF properties made with 5% of recovered HDF addition before mechanical and physical HDF boards examination, the density profile distribution was checked and the results of an average maximum SLD and an average minimum CD were gathered in Tab. 1. The

differences of top and bottom surface density from the variants were relatively small (up to 4%).

Table 1 HDF boards average maximum surface density and average minimum core density

Variant	Average max	Average min	Density difference
	kg/m <sup>3</sup>		
V0	1066	811	255
V8	1083	815	268
V16	1109	834	275
V32	1117	851	266

Density profiles distribution of all examined HDF boards produced with 5% of rHDF addition and different surface water spray amount had similar shape that is characteristic for HDF panels (Garcia et al. 2005) and there was no delamination in the middle of the produced HDF boards. Positive correlation between surface water spray amount and SLD could be observed. The highest surface density was obtained for V32 (1117 kg/m<sup>3</sup>) while the lowest for V0 (1066 kg/m<sup>3</sup>). Variants with 8 ml/m<sup>2</sup> and 16 ml/m<sup>2</sup> of surface water spray had peak density 1083 kg/m<sup>3</sup> and 1109 kg/m<sup>3</sup> respectively. The pressing parameters have a significant influence on board density profile (Wang et al. 2001), therefore, for this investigation, the continuous press parameters were kept on constant settings. However, the difference between minimum and maximum SLD was on the low level of 5%. Additionally, the difference in fibre bulk density was also relatively small (<2%), so it should not have any impact on the formation of the density profiles. An average minimum core density of the sample without surface water spray was at the level of 811 kg/m<sup>3</sup>, which was the lowest CD from examined samples while HDF board made with 32 ml/m<sup>2</sup> of the surface water spray had the highest CD – 851 kg/m<sup>3</sup>, i.e. about 5% higher. The CD of V8 and V16 were, respectively, 815 kg/m<sup>3</sup> and 834 kg/m<sup>3</sup>. Except SLD and CD also the difference between them has an impact on final panel properties (Winandy et al. 2004). The highest difference achieving ~25% (275 kg/m<sup>3</sup>) of CD comparing to SLD was for V16.

Table 2 HDF boards properties results from V0, V8, V16 and V32

Variant	Density [kg/m <sup>3</sup> ]	SD	MOR [N/mm <sup>2</sup> ]	SD	MOE [N/mm <sup>2</sup> ]	SD	IB [N/mm <sup>2</sup> ]	SD	SS [N/mm <sup>2</sup> ]	SD	MC [%]	SD	TS [%]	SD	WA [g/m <sup>2</sup> ]		FC [mg/100g]
															Top	Bottom	
V0	847	20	49.29	4.29	4053	201	0.79	0.17	1.52	0.12	5.73	0.42	37.88	1.41	203	202	4.81
V8	861	24	53.06	4.12	4536	208	0.96	0.26	1.07	0.13	5.83	0.31	33.91	1.72	185	183	4.14
V16	858	22	53.46	4.96	4668	215	0.90	0.13	1.32	0.23	5.29	0.43	37.66	1.56	212	211	4.47
V32	856	17	54.62	5.08	4526	206	1.00	0.10	1.44	0.13	5.98	0.48	36.18	1.23	196	182	4.42

That difference in variant V0 was about 7% lower comparing to V0 and V16 and was at the level of 255 kg/m<sup>3</sup> what was the smallest difference between SLD and CD. For rest of the variants – V8 and V32 it was comparable and accordingly: 268 kg/m<sup>3</sup> and 266 kg/m<sup>3</sup>. The biggest impact on the formation of the density profile might be that of the amount of surface water spray.

HDF results from all variants are gathered in Tab. 2. Additionally, standard deviations (SD) of the results are also shown.

As it can be seen in Fig. 2 showing MOR results of all variant, the samples met the minimum EN 622-5 requirements for MDF, that is  $\geq 23.00 \text{ N/mm}^2$ . What is more, the results were more than two and a half times higher than the minimum. The minimal result was obtained for board produced without surface water spray, what might have been the main factor influencing MOR. Additionally, what might have also affected the result was the lowest HDF density, which was at the level of  $847 \text{ kg/m}^3$ . According to CAI et al. (2006) on such panel properties as MOE and MOR, the panel density increase has a positive effect. Together with surface water spray, the increase of bending strength increase was also observed. Also the density of the face layers of the panels (Tab. 1), which are mainly responsible for bending features, should be considered as influencing MOR properties. The biggest increase in the value of that property was already observed for  $8 \text{ ml/m}^2$  surface water spray. The boards produced with such amount of release agent water solution had  $\sim 7\%$  higher MOR ( $53.06 \text{ N/mm}^2$ ) comparing to V0 with the density at the level of  $861 \text{ kg/m}^3$ , what was the highest result among the examined boards. In spite of a decrease in the panel density to the level of  $858 \text{ kg/m}^3$ , the further increase of the surface water spray amount to  $16 \text{ ml/m}^2$  caused a slight increase of MOR to the level of  $53.46 \text{ N/mm}^2$ . Not only does the wood based panel density have an influence on its mechanical properties, but also its moisture content (Tab. 2) – lower moisture content positively affects MDF properties (GANEV et al. 2003).

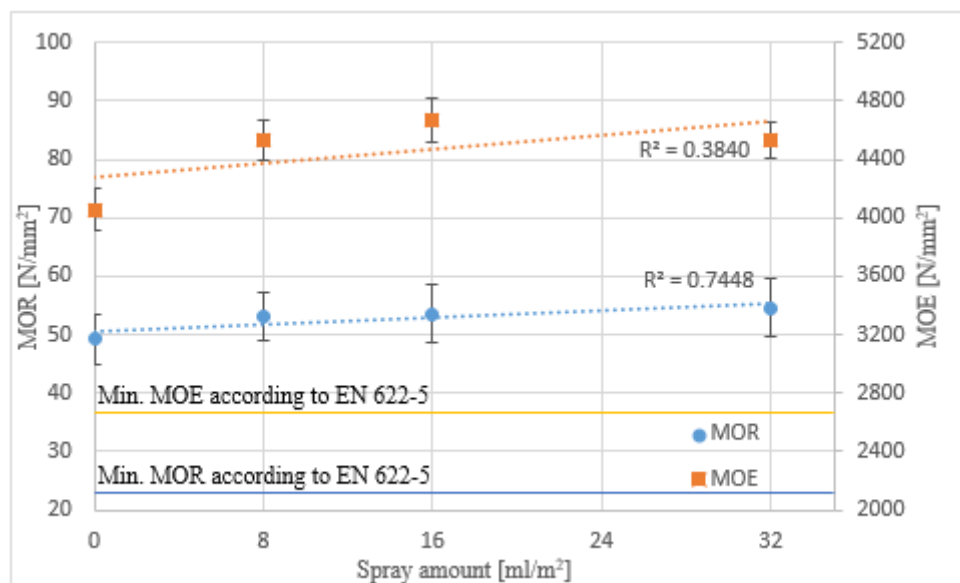


Figure 2 The surface water spray influence on HDF MOR & MOE

However, the boards produced with  $16 \text{ ml/m}^2$  of surface water spray had the lowest moisture content (5.29%), its modulus of rupture was not the highest ( $53.46 \text{ N/mm}^2$ ). On the other hand, V16 MOR was  $\sim 8\%$  higher in reference to V0 and although its density decreased slightly (for  $3 \text{ kg/m}^3$ ) comparing to V8, and a positive influence of water spray increase from  $8 \text{ ml/m}^2$  to  $16 \text{ ml/m}^2$  could be observed. Even though boards produced with  $32 \text{ ml/m}^2$  of water spray had the lowest density of the boards produced with the release agent water solution spray, and its moisture content was the highest of all the variants (5.98%–12% higher comparing to V16), its MOR was the highest. The measured result was at the level of  $54.62 \text{ N/mm}^2$ , what was higher comparing to V16 and V0, i.e. 2% and 10% respectively. That could mean, that keeping constant production parameters of HDF produced with 5% of rHDF

addition, not the panel density or its moisture content has the biggest influence, but the amount of surface water spray. There is a statistically significant difference between average values of MOR for V0 and the remaining panels, where no statistically significant differences of the average MOR values have been found for the rest samples.

The MOE was defined together with MOR examination for all of the variants and gathered in Tab. 2 and Fig. 2. In general, a positive influence on MOE result has low board moisture content (Cai et al. 2006) and additionally higher fibre density with relatively low fibres surface area resulting in an increase of the resin coverage per unit surface area (Hwang et al. 2005), which, on the other hand, is causing higher gluing per unit and also improves MDF MOE results (Hong et al. 2017). In spite of relatively high panel moisture content (5.73%), the lowest MOE was obtained for the board without surface water spray – 4053 N/mm<sup>2</sup> what was similar to MOR behaviour. The boards from V8 had 11% higher MOE result (4536 N/mm<sup>2</sup>) comparing to V0 despite having ~2% higher panel moisture content (5.83%). The further surface water spray amount raise to 16 ml/m<sup>2</sup> caused reaching the highest MOE of the examined variants at the level of 4668 N/mm<sup>2</sup>, which was ~13% more than V0. Not only water spray amount could influence that result, but also the lowest from examined panel moisture content – 5.29% and the relatively high surface peak density (1109 kg/m<sup>3</sup>) from the density profile. However, panels from V32 had the highest surface peak density (1117 kg/m<sup>3</sup>), boards with maximum surface water spray amount (32 ml/m<sup>2</sup>) had comparable result (4526 N/mm<sup>2</sup>) to V8, what was 5% less than the maximum and about 10% more than the minimum. One of the reasons causing a decrease of MOE for the V16 panel was its MC (5.98%), which was the highest of all the moisture content values for the examined panels. There is statistically significant difference between average values of MOE for V0 and remaining panels, where no statistically significant differences of average MOE values have been found for rest samples.

Regarding MDF properties, the European standard EN 622-5 specifies a minimal requirement for internal bond of boards in thickness of up to 2.5 mm to be  $\geq 0.65$  N/mm<sup>2</sup>. The results of IB were shown in Tab. 2 and visualized in Fig. 3. As it can be seen, the boards from all variants met minimal requirement and a positive influence of surface water addition on that property could be noticed. Similar to other examined mechanical properties the lowest IB was obtained for boards produced without surface water spray (V0) what was at the level of 0.79 N/mm<sup>2</sup>, while the highest result was obtained for board with maximum surface water spray amount (V32) – 1.00 N/mm<sup>2</sup> (over 20% more than the minimum). One of the parameters influencing IB results is panel core density: the higher CD – the higher IB (WONG et al. 2000). In this case, except the influence of surface water amount on IB result, the CD might have also an influence (Tab. 2). The lowest CD was measured for V0 (811 kg/m<sup>3</sup>) and the highest for V32 (851 kg/m<sup>3</sup>). On the other hand, the boards from V8 had CD on similar level 815 kg/m<sup>3</sup> to V0 while its IB was ~18% higher comparing to V0 reaching 0.96 N/mm<sup>2</sup>, additionally, it was about 4% less than the maximum. With reference to Nicewicz, Monder (2014), the influence on such result might have had relatively low fibre moisture content (10.02%) comparing to other variants. There is no statistically significant difference between average IB values for examined samples.

For the purposes of this paper, the SS was examined in order to evaluate the effect of surface water spray amount on HDF properties. Moreover some of European customers are demanding this parameter to be at the level of  $\geq 0.80$  N/mm<sup>2</sup> (Swedwood International Standard Specification of HDF 2011). Results were gathered in the Tab. 2 and shown in Fig. 3. Based on the results it can be seen that the distribution of this parameter differs from the other parameters. The highest SS from all the variants was obtained for HDF board produced with no surface water spray addition and it was at the level of 1.52 N/mm<sup>2</sup>. The highest SS from the HDF boards produced with surface water spray addition was obtained for V32 –

1.44 N/mm<sup>2</sup> what was about 5% less comparing to V0. The lowest SS was observed for V8 and was at the level of 1.07 N/mm<sup>2</sup> what was about 30% less than V0 sample and about 26% less comparing to V32. Boards from V16 had surface soundness at the level of 1.32 N/mm<sup>2</sup> what was about 19% more than the minimum SS and 13% less then maximum from V0 and 8% from V32.

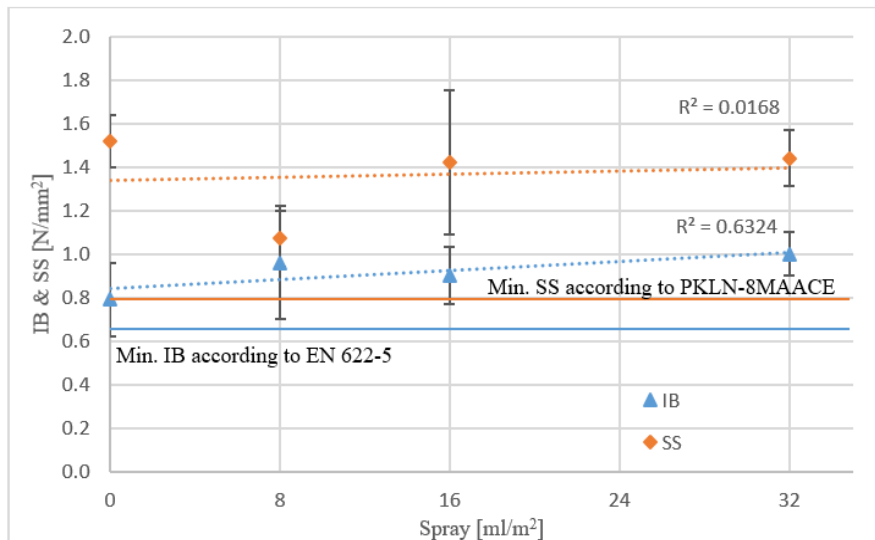


Figure 3 The surface spray amount influence on HDF (IB) and (SS)

The influence of increasing surface water spray amount on increasing SS could be notice. It might have been caused by better heat transfer and curing the resin and additionally, based on literature, the performance of SS may be also dependent on the density profile and its SLD (Wong et al. 2000). This could be an additional explanation of the behaviour of variants V8, V16 and V30 where the SS was increasing together with a slight SLD increase, while the boards from V0 had the lowest SLD, which could mean that not only was SLD influencing this parameter but so was the surface waters spraying amount. The highest fibre moisture content (11.17%) could have a positive impact on the highest performance in V0. There is a statistically significant difference between average values of SS between V8 and V0 and V32, whereas there are no statistically significant differences of average SS for V16 and the remaining samples.

The results of TS are shown in Tab. 2 and visualized in Fig. 4. As can be seen, the boards from all variants met the minimal requirement of EN 622-5. What is more, a positive influence of the surface water addition on that property could be noticed. On the other hand, some furniture companies require stricter swelling e.g. due to the fact, that IKEA Industry is selling their goods all over the world ([www.ikea.pl](http://www.ikea.pl)), their demand for TS is to use HDF boards with swelling 24h <35% for furniture production (Swedwood International Standard Specification of HDF 2011) and, considering such a requirement, only boards from V8 variant could meet such specifications. The relations between the board moisture content and the swelling is rather proportional (Trechsel et al. 2010); in order to prove it, there have been several researches performed which confirm that together with an increase in the content of wood-based panels moisture, the swelling decreases (Carll 1996). Although the panel moisture content of boards produced without surface water spray (V0) was not the lowest (5.73%), its TS was the highest – 37.88%, while addition of only 8 ml/m<sup>2</sup> of surface water spray caused a drop of thickness swelling of over 10% to the level of 33.91%, with a board moisture content (5.83%) comparable to V0. The further surface water spray amount increase did not cause further TS reduction. The board from V16, which moisture content was the



lowest (5.29%), had the thickness swelling after 24 h at the level of 37.66%, which was comparable to V0 and about 10% higher than minimum from V8. This could mean that not only panel moisture content has an influence on final TS, but also the surface water spray amount. The boards with maximum examined surface water spray amount (V32) had thickness swelling 24 h at the level of 36.18%, which was about 5% less comparing to V0 and over 6% more comparing to V8, despite having the highest panel moisture content (5.98%). There is a statistically significant difference between average values of TS between V8 and V0 and V16, where no statistically significant differences of average TS for the remaining samples.

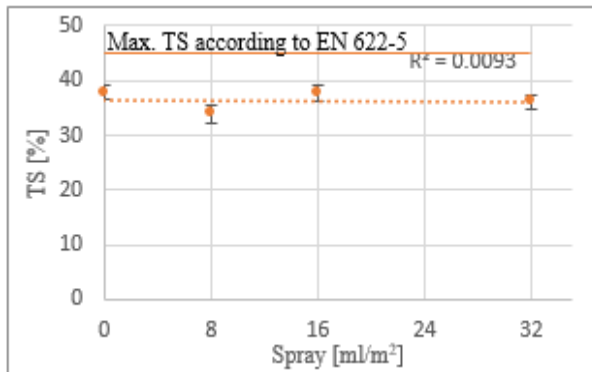


Figure 4 The surface spray amount influence on HDF TS

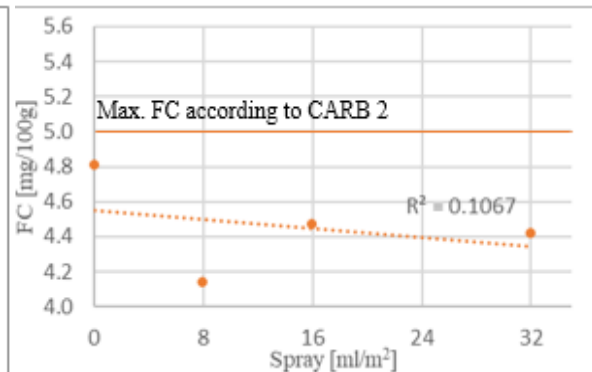


Figure 5 The surface spray amount influence on HDF FC

As it can be seen in Tab. 2 and Fig. 5, all the produced HDF boards met that California Air Resources Board standard requirement of formaldehyde content (IOS- MAT- 0003), however surface water spray addition influenced FC decrease. A board from the V0 that was produced without surface water spray had the highest formaldehyde content (4.81 mg/100g) while the lowest was obtained for boards produced with 8 ml/m<sup>2</sup> of surface water spray – 4.14 mg/100g (i.e. 14% less). Further addition of surface water amount did not cause further FC decrease and FC from V16 had the highest result (4.47 mg/100g) from variants with surface water spray that was higher than the minimum for about 7% but lower than the maximum FC from V0 also for about 7%. The boards with 32 ml/m<sup>2</sup> of surface water spray amount had formaldehyde content at the level of 4.42 mg/100g, which is slightly lower than the maximum and about 6% more than the minimum for V8. One of the factors influencing wood-based panel formaldehyde content may be the moisture content of wooden raw material before press (Aydin et al. 2006). This could influence better heat transfer during the pressing process and better resin curing, which could explain the highest FC for V0 and decreasing FC together with surface water spray addition.

The results for the top and the bottom surface water absorption (WA) are shown in Fig. 6. The results for the bottom side of the board were minimally (~1%) lower comparing to the top side, except for V32, where it was about 7% lower. Depending on the tested variant, the value of this parameter was similar to the value of thickness swelling after 24h for the same board variant. Despite one of the HIGHEST SLD (1109 kg/m<sup>3</sup>) the highest top and bottom surface water absorption occurred in the board from V16 – 212 g/m<sup>2</sup> and 211 g/m<sup>2</sup>. The result might have been influenced by the lowest panel moisture content. The lowest top and bottom WA was measured for V8 that was 185 and 183 g/m<sup>2</sup> and was about 13% less than the maximum WA from V16. Boards with the highest panel moisture content and the highest surface density peak had top and bottom surface water absorption at the level of 196 and 182 g/m<sup>2</sup> what was in average about 3% more than the minimum and about 11% less than the maximum WA result. The boards without surface water spray represented relatively high

WA, which was at the level of top 203 g/m<sup>2</sup> and bottom 202 g/m<sup>2</sup>. It could mean that surface water addition is positively influencing surface water absorption reduction.

Table 3 HDF surface roughness results

Variant	Roughness Ra [μm]	
	Top side	Bottom side
V0	4.41	4.69
V8	3.46	3.84
V16	3.32	3.58
V32	3.04	3.41

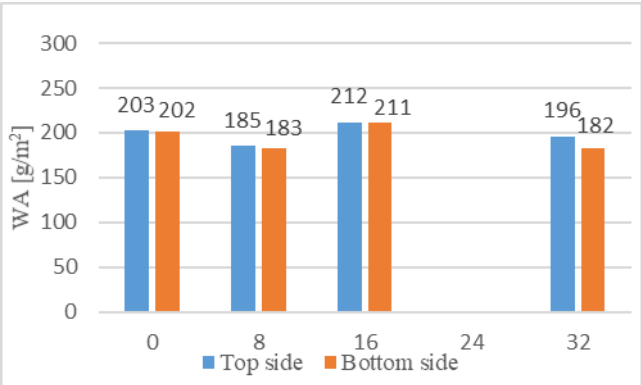


Fig. 6 The surface spray amount influence on HDF WA

For better understanding of the influence of surface water spray amount on HDF properties produced with 5% of rHDF addition, the surface roughness was also defined and the result are shown in Tab. 3. According to Bialecki et al. 2008, increased roughness of HDF surface is one of the factors influencing the increase of sealing materials consumption during lacquering, which can be crucial for some of the furniture producers. Based on results it can be seen that bottom surface had for about 8% higher roughness in reference to top side of the board. According to Nicewicz, Sala (2014), the roughness of the board could be one of the factors influencing the results of surface water absorption. These results can also mean that the bottom side of HDF was more open. There has been a visible impact of surface water amount increase on surface roughness decrease and better surface closing, what might have been caused by improved heat transfer in variants with water spray addition. The highest roughness was measured for top and bottom surfaces accordingly 4.41 μm and 4.69 μm, where there has been no water spray applied. The addition of 8 ml/m<sup>2</sup> of water spray caused a decrease of the top surface roughness for about 12% to 3.46 μm and bottom for about 18% to 3.84 μm. Doubling the amount of water spray to 16 ml/m<sup>2</sup> caused a drop of the top roughness to 3.32 μm and the bottom roughness to 3.58 μm, which was lower than the minimum by about 24%. The lowest top and bottom surface roughness was measured for the variant with the highest surface water spray amount in V32, and it was, respectively: 3.04 μm and 3.41 μm. Surface of V32 was over 30% more “closed” comparing to V0. The influence of HDF moisture content or density profile shape was not observed.

**PART 2: 3<sup>rd</sup> press heating section temperature**

**HDF results**

HDF results from all variants were gathered in the Tab. 4. Additionally, standard deviations (SD) of the results were also shown.

The panel density difference between the minimum (V75 – 861 kg/m<sup>3</sup>) and the maximum (V45 – 869 kg/m<sup>3</sup>) was less than 1% so it should not have any influence on HDF properties. V60 board density was at the level of 864 kg/m<sup>3</sup>. As it can be seen in the Tab. 4, the panel density change could be connected with board moisture content. Together with panel moisture content decrease, panel density was also slightly decreasing.

Table 4 HDF boards properties results from V45, V60 and V75

Variant	Density [kg/m <sup>3</sup> ]	SD	MOR [N/mm <sup>2</sup> ]		MOE [N/mm <sup>2</sup> ]		IB [N/mm <sup>2</sup> ]		SS [N/mm <sup>2</sup> ]		MC [%]		TS [%]		SD		WA [g/m <sup>2</sup> ]		FC [mg/100g]	
			SD	SD	SD	SD	SD	SD	SD	SD	SD	SD	SD	SD	SD	SD	SD	SD		SD
V45	869	20	50.7	3.5	4142	192	1.05	0.20	1.40	0.15	6.4	0.3	31.05	1.28	197	202	5.42			
V60	864	17	51.4	4.0	4743	186	0.96	0.18	1.12	0.23	6.2	0.3	33.00	1.47	203	228	5.30			
V75	861	18	52.7	3.9	4729	195	1.05	0.22	1.17	0.13	5.8	0.4	31.86	2.04	224	208	4.60			

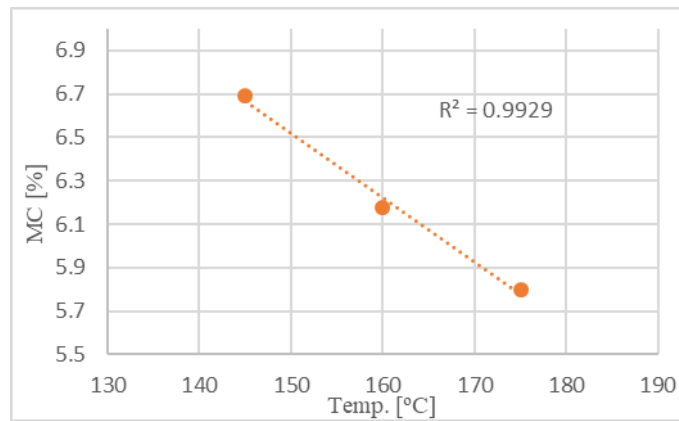


Fig. 7 Pressing temperature influence on HDF MC

The crucial aspect factor in the hot pressing process is to bring energy to the pressed material. It may be achieved by, e.g. increasing the process duration time, pressure and/or temperature. The higher the temperature is, the more energy is brought during hot pressing operation. Additionally, the mat core temperature increases, which helps better resin curing and translates into better performance of MDF (Koros et al. 2011; Thoemen, Humphrey 2006; Winandy, Krzysik 2007). Fig. 7 visualizes the moisture content of individual board variants. As it can be seen, the highest panel moisture content was achieved for V45 – 6.7%. An increase in the pressing temperature had a strong negative correlation with a moisture content decrease. The V60 board had ~ 8% lower moisture content (6.2%) compared to the V45 board, while the V75 board showed a further drop in moisture content to the level of 5.8%. It was ~ 13% and ~ 6% less compared to, accordingly, V45 and V60 boards. It could mean that a higher 3<sup>rd</sup> press heating temperature resulted in more water evaporating from the pressed material. Such a difference in the board moisture content may have an influence on HDF properties similar to that on other wood-based materials (Bekhta, Niemz 2009; Sala et al. 2020; Khalil et al. 2008; Wu, Suchsland 1997).

MOR results are shown in Fig. 8. All of variant samples met the minimum MDF requirements of the EN 622-5 standard. The achieved results were more than two times higher than the norm. In MDF production increasing press temperature has statistically significant effect on MOR increase. As it turned out based on Fig. 8 data, the temperature of the 3<sup>rd</sup> heating section of the press in HDF production with 5% addition of rHDF has a similar relation, i.e. the higher the temperature, the higher the MOR value. The minimal MOR was

achieved for V45 (50.67 N/mm<sup>2</sup>). Boards from V60 had MOR at the level of 51.43 N/mm<sup>2</sup> (i.e. about 2% more than V45). A further press temperature increase to 175°C resulted in bending strength increase by next 2% to the level of 52.72 N/mm<sup>2</sup> (i.e. around 4% more than the minimum). Curing is the key to the bonding because MUF resin requires acidic environment and proper temperature for the curing process (Campana et al. 2018; Koros et al. 2011; Zheng et al. 2011). MOR results may improve thanks to better resin curing together with 3<sup>rd</sup> press heating section temperature increase, but also thanks to lower moisture of the panel. There were no statistically significant differences of MOR average values found for the variants.

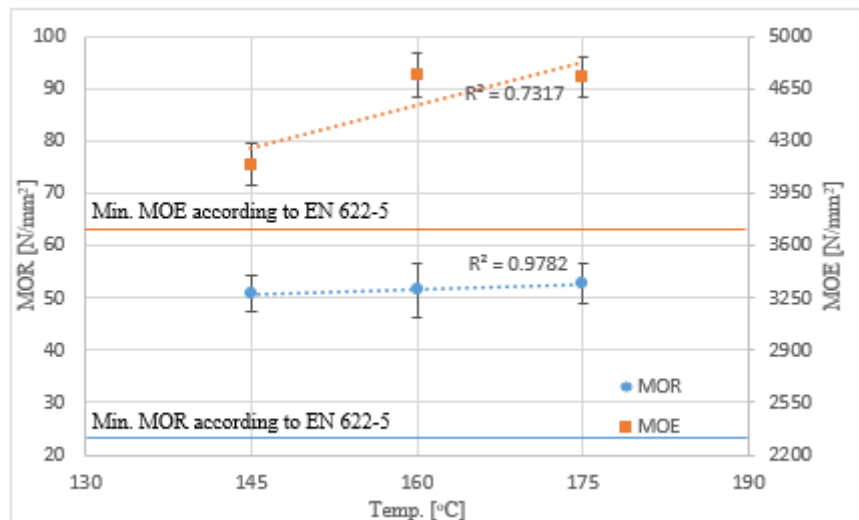


Figure 8 Pressing temperature influence on HDF MOR and MOE

Together with MOR, the MOE was defined and the results are presented in Tab. 4 and Fig. 8. The boards from V45 had MOE at the level of 4142 N/mm<sup>2</sup>, which was minimum. Increasing 3<sup>rd</sup> press heating section temperature to 160°C caused an increase in MOE by about 13% to the level of 4743 N/mm<sup>2</sup>, what was the maximum. The further press temperature increase did not cause a MOE increase. Boards from V75 had comparable to V60 MOE, however slightly lower and it was at the level of 4729 N/mm<sup>2</sup>. V75 board moisture content was the lowest (5.8%) and based on Sala et al. (2020), lowering panel moisture content results in a MOE increase. It could mean that V60 temperature was the most optimal setup for 2.5 mm board with 5% of rHDF addition produced on the press. There is statistically significant difference between average values of MOE for V45 and the remaining panels where no statistically significant differences of average MOE values have been found for the remaining variant samples.

IB results were gathered in the Tab. 4 and shown in the Fig. 9. The boards from all variants met minimal requirement in case of IB. Both V45 and V75 had the highest IB result at the level of 1.05 N/mm<sup>2</sup>. Minimal IB was achieved for V60 – 0.96 N/mm<sup>2</sup> that was ~9% less comparing to maximum. Considering MDF boards IB is increasing together with pressing temperature increase (Gul et al. 2017), on the other hand, the IB of MDF made of eucalyptus wood, depending on pressing parameters, may deteriorate (Kargarfard, Latibari 2014). On such results of HDF boards rHDF addition could have an impact. It could mean that both fibre preparation condition and pressing variables may be adjusted to enable reaching required quality of the fibres and boards. There were no statistically significant differences of IB average values found for the variants.

Surface soundness results are shown in Tab. 4 and in Fig. 9. The boards from all the variants met the minimal requirement of Swedwood (PKLN-8MAACE 2011). The V45 had the highest SS – at the level of 1.40 N/mm<sup>2</sup>.

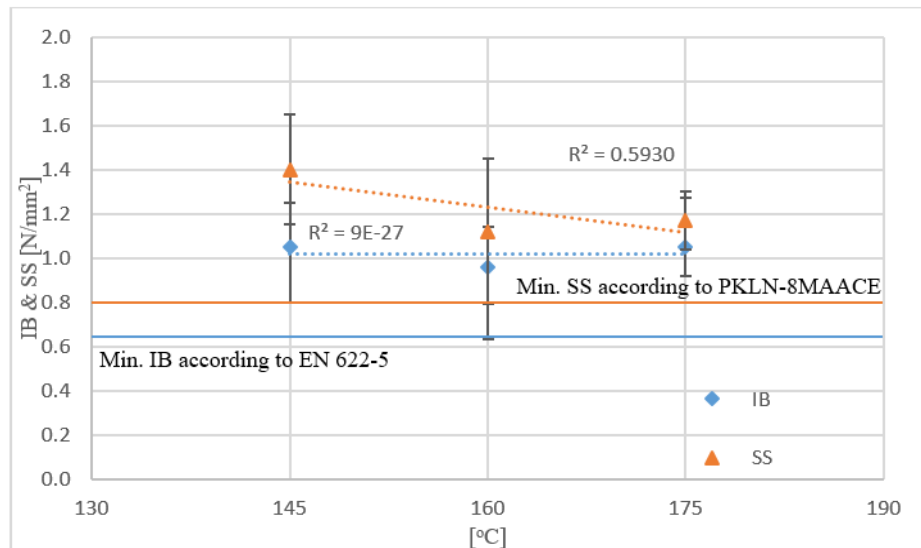


Figure 9 Pressing temperature influence on HDF IB and SS

An increase in 3<sup>rd</sup> press heating section temperature to 160°C resulted in SS decrease to 1.12 N/mm<sup>2</sup>, what was the lowest and 20% less comparing to V45. The boards from V75 had SS at the level of 1.17 N/mm<sup>2</sup>, that was comparable to V60 and 17% lower regarding V45. It could mean that an increase in the pressing temperature from 145°C to 175°C has a negative impact on the surface, which may be connected with increasing resin hydrolysis rate with the temperature increases (Jeremejeff 2012), that leads to weaken glue bonding. Additionally, the higher pressing temperatures degrades fibre quality (Winandy, Krzysik 2007) and considering, that fibre quality is directly responsible for board quality, it could be the reason for HDF SS reduction. There were no statistically significant differences of SS average values found for the tested variants.

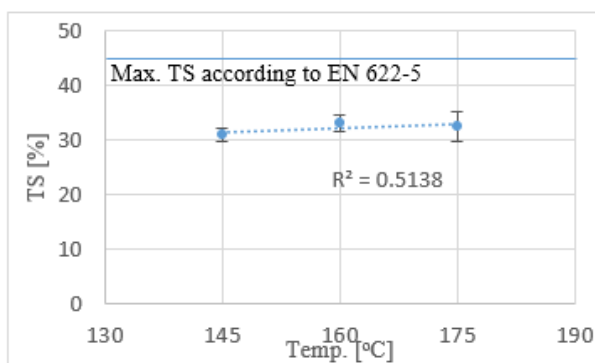


Figure 10 Pressing temperature influence on HDF TS

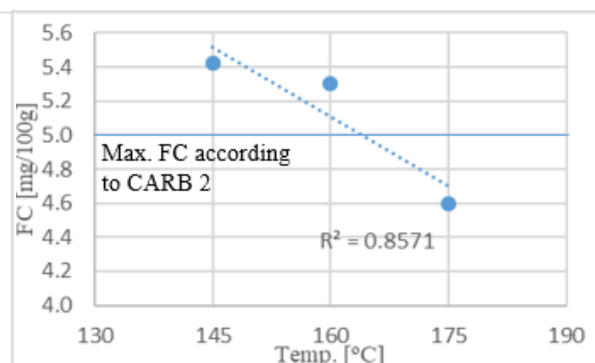


Figure 11 Pressing temperature influence on HDF FC

TS 24h results were shown in the Tab. 4 and visualized in the Fig. 10. All board variants met EN 622-5 minimal requirement of TS24. The highest swelling was for V60 – 33.00%. 3<sup>rd</sup> press heating section temperature increase to 175°C caused about 2% reduction of thickness swelling to the level of 32.50%. The boards from V45 had the lowest swelling, which was at the level of 31.04%, what was 6% lower than the maximum. One of the factors

which cause minimal swelling 24h could be the highest panel moisture content. However, despite the lowest moisture content in the V75 panel, its TS 24h was not the highest. It could mean that pressing temperature had more influence on HDF TS 24h than MC. There were no statistically significant differences of TS24 average values found for the variants.

Based on the data from Fig. 11 showing formaldehyde content, it could be stated that only V75 met the requirement. Maximum FC was V45 with the result of 5.42 mg/100g. There was quite strong negative correlation between FC and the 3<sup>rd</sup> press heating section temperature increase. The result for V60 boards was about 2% lower (5.30 mg/100g). Further pressing temperature increase enabled V75 to be within the limit of FC having content at the level of 4.60 mg/100g what was 15% less than the maximum. The higher the temperature, the better and faster the resin curing that reduces free formaldehyde in wood-based panels. Additionally, together with a temperature increase, a decrease in wood pH can be observed (Latibari et al. 2012; Roffael 2012). As growing fibre acidity is enhancing hardening the resin, less free formaldehyde remains in ready wood-based panel. This might be the reason behind a drop of HDF formaldehyde content as well as an increase of 3<sup>rd</sup> press heating section temperature.

In order to better evaluate 3<sup>rd</sup> press heating section temperature influence on HDF boards produced with 5% of rHDF addition, the top and bottom surface WA was also examined. The results are presented in Tab. 4. Regarding the top surface WA, it was increasing together with an increase in the pressing temperature. Similar correlation was found for MDF made of hardwood species during pressing temperature increase from 160 to 200°C (Mihajlova et al. 2014). The lowest WA was recorded for a board from V1 (197 g/m<sup>2</sup>). As high as 15°C temperature increase caused 3% WA increase to the level of 203 g/m<sup>2</sup>. The highest surface WA was recorded for a board from V75 – 224 g/m<sup>2</sup>, which was 12% and 9% more than V45 and V60, respectively. Regarding the bottom surface, WA and V45 had the lowest sorption – 202 g/m<sup>2</sup>. A 15°C temperature increase caused a 11% WA increase to the level of 228 g/m<sup>2</sup>, which was the highest from bottom WA. A further pressing temperature increase caused a WA decrease in V75 to the level of 208 g/m<sup>2</sup> (3% more comparing to V45 and 9% less comparing to V60). Factors which can have an impact on the results of board moisture content include: higher WA, lower WA, and surface glue hydrolysis that enables easier surface water penetration. Additionally, surface roughness was measured, however no significant correlations between Ra and 3<sup>rd</sup> press heating section temperature increase were found.

## CONCLUSIONS

Based on the results of this study, the following conclusions can be drawn, according to the HDF panels produced with use of 5% of recycled HDF:

### PART 1 The surface water spray amount

Surface water spray amount has an impact on the density profile shape of industrial HDF. Together with a water spray amount increase, the surface peak density is increasing by up to 5%.

Together with surface water spray amount increase from 0 ml/m<sup>2</sup> to 32 ml/m<sup>2</sup>, the MOR of industrial HDF is increasing by up to 10%.

An addition of 16 ml/m<sup>2</sup> surface water spray amount for industrial HDF production causes MOE increase for about 13% comparing to boards produced without surface water spray addition.

Together with surface water spray amount increase from 0 ml/m<sup>2</sup> to 32 ml/m<sup>2</sup> the IB of industrial HDF is increasing by up to 21%.

An addition of surface water spray amount causes decrease of SS of HDF by up to 30% for V8. Together with surface water spray amount increase from 8 ml/m<sup>2</sup> to 32 ml/m<sup>2</sup> the SS of industrial HDF is increasing by up to 26%.

An addition of surface water spray amount causes decrease of TS24 of HDF by up to 11% for V8. Further surface water spray amount increase does not cause significant TS24 change.

An addition of surface water spray amount causes decrease of top and bottom WA of HDF by up to 9% for V8.

Together with surface water spray amount increase from 0 ml/m<sup>2</sup> to 32 ml/m<sup>2</sup> the surface roughness of industrial HDF is decreasing by up to 31% for top and by up to 27% for bottom side of the board better heat transfer and surface closing.

Addition of surface water spray amount causes decrease of formaldehyde content of HDF for up to 14% for V8 due to better heat transfer and resin curing.

PART 2 3<sup>rd</sup> press heating section temperature

Together with 3<sup>rd</sup> press heating section temperature increase from 145°C to 175°C there is a negative linear correlation with MC causing up to 13% drop in HDF MC.

Together with 3<sup>rd</sup> press heating section temperature increase from 145°C to 175°C there is a positive linear correlation with MOR causing up to 4% increase in HDF MOR.

Together with 3<sup>rd</sup> press heating section temperature increase from 145°C to 175°C there is a positive linear correlation with MOE causing about 13% increase in HDF MOE.

Increasing of 3<sup>rd</sup> press heating section temperature from 145°C to 160°C causes IB reduction for up to 9% of HDF board.

Increasing of 3<sup>rd</sup> press heating section temperature from 145°C to 160°C causes a SS reduction of up to 20% of HDF board.

Increasing of 3<sup>rd</sup> press heating section temperature from 145°C to 160°C causes TS 24h increase of up to 6% of HDF board.

Increasing of 3<sup>rd</sup> press heating section temperature causes a WA increase of about 12% of HDF surface.

Together with 3<sup>rd</sup> press heating section temperature increase from 145°C to 175°C there is a negative linear correlation with FC causing up to 15% drop in HDF FC.

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**Streszczenie:** *Wpływ natrysku oraz temperatury prasowania na właściwości płyt pilśniowych suchoformowanych wysokiej gęstości.* Celem badań było określenie wpływu ilości natrysku wody oraz temperatury 3-ciej sekcji grzewczej prasy, jako parametrów procesowych, na właściwości mechaniczne i fizyczne ultra cienkich płyt (2,5 mm) włóknistych wysokiej gęstości (HDF), wytwarzanych z 5% udziałem włókien poużytkowych (rHDF). W pierwszej części użyto natrysku wody na powierzchnię górną i dolną prasowanego materiału w ilościach: 0 ml/m<sup>2</sup>, 8 ml/m<sup>2</sup>, 16 ml/m<sup>2</sup> i 32 ml/m<sup>2</sup>. W drugiej części zastosowano zmienne temperatury 3-ciej sekcji grzewczej przemysłowej prasy ciągłego działania, tj.: 145°C, 160°C i 175°C. Po przebadaniu płyt z różnym natryskiem wody na powierzchnię, zauważono pozytywną liniową zależność dla MOR – wzrost do 10% porównując skrajne badane warianty. Podobnie było w przypadku chropowatości powierzchni, która maleje o 31%. Natrysk wody na powierzchnię poprawia IB do 21% oraz obniża WA o 9% porównując ze sobą warianty 0 i 8 ml/m<sup>2</sup>. W przypadku wpływu temperatury 3-ciej sekcji grzewczej prasy to takie parametry mechaniczne jak MOR i MOE poprawiają się wraz ze wzrostem tej temperatury, a inne jak: IB czy SS pogarszają.

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