Drewno 2015, Vol. 58, No. 194
DOI: 10.12841/wood.1644-3985.089.04

Dorota Dukarska, Monika Bartkowiak, Agata Stachowiak-Wencek

WHITE MUSTARD STRAW AS AN ALTERNATIVE RAW MATERIAL IN THE MANUFACTURE OF PARTICLEBOARDS RESINATED WITH DIFFERENT AMOUNTS OF UREA-FORMALDEHYDE RESIN

In this work the optimum resination rate of white mustard straw particles with UF resin in the production of straw particleboards was investigated. The resination rates used in this study were 10, 12 and 14%. For the selected resination rate, the possibility of reducing the density of the straw particleboards was also determined. In order to evaluate the hygienic parameters of the experimental boards, the formaldehyde content and volatile organic compounds (VOC) were determined. Moreover, using a thermogravimetric analysis (TGA) the boards' disposal options by means of burning or co-incineration were investigated. The study results showed that a 10% resination rate enabled the production of white mustard particleboards of type P1 and P2, while the simultaneous reduction in their density to 600 kg/m^3 limited their application to dry conditions only, i.e. boards of P1 type. Thermogravimetric analysis revealed a variable thermal performance of the studied boards. The pine particleboards showed a higher thermal resistance, however, up to a temperature of 750°C, the samples of the experimental boards underwent a similar process of thermal destruction.

Keywords: white mustard straw, particleboards, mechanical properties, VOC, thermogravimetric analysis

Introduction

Wood availability and its price largely affect the economic condition of the timber industry. Increasing competition for wood, related to enhanced wood consumption for energy purposes, has resulted in higher wood prices and has led to difficulties for producers of wood-based materials in obtaining adequate quantities

---

Dorota Dukarska (*ddukar@up.poznan.pl*), Department of Wood Based Materials, Faculty of Wood Technology, Poznań University of Life Sciences, Poznan, Poland; Monika Bartkowiak (*libra10@poczta.onet.pl*), Agata Stachowiak-Wencek (*agatas@up.poznan.pl*), Institute of Chemical Wood Technology, Faculty of Wood Technology, Poznań University of Life Sciences, Poznan, Poland

of raw materials. Therefore, some steps have been taken with the aim of using wood more efficiently and sustainably, e.g. by applying substitutes in the form of tree species not used so far in the particleboard industry, such as alder [Nemli 2003] or even agricultural biomass. For many years, there has been a growing interest in the possibility of using biomass for energy purposes. It is currently the largest potential source of energy in the world. Biomass processed into briquettes or pellets is a substitute for non-renewable fuels. In addition, a rapidly growing wood processing sector, which includes the production of particleboards, MDFs and other wood-based materials, has created the need for the effective disposal of post-production waste, 90% of which is composed of a biomass in the form of comminuted wood. Its disposal by means of incineration or co-incineration in boilers of a special design, provides an additional source of energy for plants producing such materials. Numerous studies carried out so far have demonstrated that the waste of annual plants can serve as a wood substitute for the wood-based board industry, and paper industry [Boquillon et al. 2004; Guler, Ozen 2004; Dziurka et al. 2005; Dukarska et al. 2006; Czarnecki, Dukarska 2010; Dziurka et al. 2010; Azizi et al. 2011; Li et al. 2011; Dukarska et al. 2012; Park et al. 2012; Bekhta et al. 2013]. This particularly concerns cereal straw, with EU overproduction amounting to 140 million tons, 70% of which can be used for industrial purposes. Some of undoubted advantages of this type of material include the possibility of obtaining large quantities every year, its wood-like chemical composition and its morphology which facilitates felting. On the other hand, the seasonal availability of straw and the resulting irregular supply, seriously restricts its industrial application. Therefore, the feasibility of alternative crops, harvested in different periods to cereals, for particleboard production, has been investigated. An example of such a plant is white mustard *(Sinapis alba),* known for its high yield, rapid growth in a short growing season (80–125 days) and production of large amounts of biomass. Currently, mustard cultivation is most popular in Europe, Asia, Africa and North America. According to FAO STAT reports [2012], the largest producers of mustard in 2012 were Nepal – 145.2 thousand tons, Canada 118.4 thousand tons, Myanmar – 68 thousand tons and the Russian Federation – 41.5 thousand tons. Mustard is a multi-purpose plant. It is grown mainly for seeds, used in the food, pharmaceutical, and cosmetic industries, and as a stubble crop. It is classified as an energy crop, although it is less economically important than rape. Recent years have brought a markedly higher interest in mustard cultivation and the possibility of its further applications in various fields. This is due to the above-mentioned advantages as well as the low price of the seeds, the possibility of using mustard as an energy crop, and new prospects offering varieties of improved seed oil composition, similar to rapeseed oil [Piętka 2007]. It can therefore be expected that alternative plants, including mustard, will, to some extent, replace traditional crops [Suleimenov et al. 2005; Sawicka, Kotiuk 2007]. Dukarska et al. [2011] investigated the possibility of using white mustard straw as a substitute for wood particles in the production of particleboards. This study also determined the usefulness of mustard straw in the manufacturing process, by comparing its chemical composition with wood and other often studied plant species (wheat and rape) and by comparing their fractional composition and dimensional analysis. Previous works have shown that the chemical composition of mustard is comparable to that of wood and rape straw. Moreover, the shape factors of the straw particles (slenderness and flatness) are similar to the parameters of the particles from the particleboard core layer. Mustard straw particles are more slender than wood particles, which may positively affect the board structure by reducing empty spaces and improving the board bending strength. Tests performed on wood and straw boards with a different share of straw particles resinated with UF resin confirmed that the addition of mustard particles to the mixture of wood particles did not significantly affect the board bending strength and modulus of elasticity. However, a reduced internal bond was observed, particularly when the straw share exceeded 25%. Nevertheless, the boards containing even 100% mustard straw particles met the requirements of the EN 312 standard for boards intended for general use in dry conditions. Reducing the straw content to 75% allowed for the production of P2 boards, i.e. boards intended for interior design, including furniture, and for use in dry conditions.

With the above findings in mind, the aim of this study was to determine the optimal resination rate of white mustard straw particles (*Sinapis alba*) during the production of boards resinated with urea-formaldehyde resin, and to analyze the process of the boards' thermal decomposition during incineration.

Materials and methods

The experimental boards were manufactured from industrial pine particles and white mustard (*Sinapis alba*) straw particles, obtained from a farm in western Poland. The straw particles were generated in the laboratory, by a single-stage fragmentation on a shredder cutter. The full characteristics of white mustard straw and wood particles were provided in a previous work by Dukarska et al. [2011]. They were glued with an urea-formaldehyde resin (UF) produced by Silekol (Kedzierzyn-Kozle, Poland) with a viscosity of 554 mPa s, a density of 1.282 kg/m^3, assumed amount of dry substances 66%, pH 7.85, and 65 s gel time at 100°C. The curing agent, which was a 20% ammonium nitrate (NH_4NO_3) solution, was used to the amount of 2% of dry weight of the UF resin.

The experimental boards were produced in a laboratory: they were single layer boards with a density of 700 kg/m^3, a thickness of 12 mm and resination rate of 10, 12 and 14%. Taking into account the considerable interest of the particleboard industry in low density materials, boards were also manufactured with a density reduced to 600 and 500 kg/m^3, and a resination rate determined on the basis of the studies discussed above. Pressing was performed at 200°C, at a unit pressure of 2.5 N/mm^2 for 22 s/mm of the board thickness. The control boards were pine (*Pinus sylvestris*) particleboards, manufactured in the same conditions.

The resulting experimental boards were tested for their physical and mechanical properties, in accordance with applicable technical standards, and the following parameters were determined: the modulus of rigidity (MOR), modulus of elasticity (MOE) in accordance with EN 310, internal bond (IB) according to EN 319, swelling after 24 hours of soaking in water (TS) according to EN 317 as well as water absorption (WA), and free formaldehyde content by perforator method according to EN 120.

Studies on the VOC emissions were conducted on the boards manufactured from straw and wood particles with resination rates and densities selected based on the physico-mechanical properties of boards 30 days (±5) after they had been produced. The tests were performed in a glass chamber of 0.025 m^3, in which the following conditions were maintained: temperature 23 ±2°C, relative humidity 50 ±5%, air exchange rate 0.5 dm^3/h, and chamber loading 0.005 m^2/m^3. Air samples were collected into tubes filled with Tenax TA at 120 mg (35/60 mesh, by Alltech). In each case, three simultaneous air samples of 1000 ml were collected at a rate of 100 ml/min. Analytes adsorbed on the Tenax TA were released thermally and then determined by gas chromatography coupled with mass spectrometry. The GC/MS parameters are presented in table 1. Individual compounds were identified by comparing the obtained mass spectra with the spectra stored at the NIST MS Search library – program version 1.7 and were then confirmed by juxtaposing the mass spectra and retention times of the identified compounds with the spectra and retention times of the appropriate standards. Quantitative analyses of the VOCs emitted from the examined wood surfaces were carried out by adding the 4-bromofluorobenzene standard (Supelco).

Table 1. Operating conditions of TD/GC/MS

Elements of measuring system	Parameters
Injector	Thermal desorber connected to sorption microtrap; purging gas: argon at 20 m^3/min; purge time: 5 min
Microtrap	Sorbent: 80 mg Tenax TA/30 mg Carbosieve III; desorption temperature: 250°C for 90 s
Gas chromatograph	TRACE GC, Thermo Finnigan
Column	RTX – 624 Restek Corporation, 60 m × 0.32 mm ID; D_f – 1.8 µm: 6% cyanopropylphenyl, 94% dimethylpolyoxosilane
Detector	Mass spectrometer (SCAN: 10 – 350)
Carrier gas	Helium: 100 kPa, ~2 cm^3/min
Temperature settings	40°C for 2min, 7°C/min to 200°C, 10°C/min to 230°C, 230°C for 20 min

In order to analyze the thermal decomposition of the experimental boards containing mustard straw particles during incineration, a thermogravimetric analysis was carried out, using a SETARAM Labsys^{TM} thermobalance, with a final analysis temperature of 750°C, increasing at a rate of 5°C/min. The analysis was conducted in the presence of helium flowing through the reaction chamber at a rate of 2 dm^3/h, while the mass of each sample was 20 ±1 mg. The thermal analysis of the tested samples was recorded as thermograms which included thermogravimetric curves (TG) and differential thermogravimetric curves (DTG).

Results and discussion

The physical and mechanical properties of the experimental boards made of wood and mustard straw particles, with regards to their UF resination rate, are presented in table 2 and in fig. 1. The symbols "a, b, c, d" denote the groups of homogeneous means identified based on a *post hoc* analysis of the Tukey's test. The data in table 2 indicate that the use of mustard straw particles as a substitute for wood particles resulted in an enhanced modulus of rigidity (MOR). The values of the modulus of rigidity, obtained for the resination rate reduced to 10%, exceeded the parameters of the boards made of wood particles alone, and met the requirements of the EN 312 standard for general-purpose P1 boards (required value 12.5 N/mm^2), and P2 boards for interior design, including furniture (required value 13.0 N/mm^2), used in dry conditions. *Post hoc* tests confirmed that increasing the resination rate of the straw boards did not significantly affect the MOR (homogeneous group "a"). However, a slightly greater effect of the resination rate on the rigidity of the investigated straw boards was observed. Based on *post-hoc* tests, it was found that significant differences in the mean MOE values were perceived only when the resination rate exceeded 12%.

Table 2. Properties of the experimental boards depending on resination rate of UF resin

Z*	Kind of particles	MOR	MOE	TS	WA
[%]		[N/mm^2]		[%]	
10	wood	12.8 (1.38)** b	2750 (225) a	51.0 (4.56) b	104.6 (11.0) bc
12		13.1 (2.77) b	3170 (111) cd	40.8 (3.45) a	88.5 (4.84) a
14		15.8 (2.76) a	2890 (387) ab	22.14(3.68) c	91.0 (7.69) a
10	straw	16.0 (1.11) a	2980 (180) abc	62.1 (2.35) d	113.8 (8.99) c
12		16.2 (1.20) a	3050 (245) bc	52.6 (4.07) b	100.8 (11.21) a
14		16.8 (1.21) a	3360 (305) d	39.2 (3.87) a	85.6 (8.54) a

*Z – resination rate of board, ** – standard deviation, a, b, c… – homogenus groups, MOR – modulus of rigidity, MOE – modulus of elasticity, TS – thickness swelling,WA – water absorption; density of the particleboards – 700 kg/m^3

It can therefore be concluded that increasing the resination rate from 10 to 12% is statistically unjustifiable. Despite the observed changes in the mean MOE values, the boards, as in the case of the modulus of rigidity, met the requirements for P2 boards (required value 1800 N/mm^2). The results received for the internal bond perpendicular to the board planes differed considerably, as presented in fig. 1. As might be expected, replacing the pine particles with mustard straw particles resulted in a significant reduction in the internal bond and significantly different mean IB values (ANOVA: for resination rate – $F(2;84) = 31.1$, $p < 0.0001$, for raw material $F(1;84) = 289.3$, $p < 0.0001$). As the internal bond is one of the factors affecting the strength of furniture joints, it is important that the boards intended for furniture production meet the relevant requirements of the EN 312 standard, prepared for general purpose boards used in dry conditions.

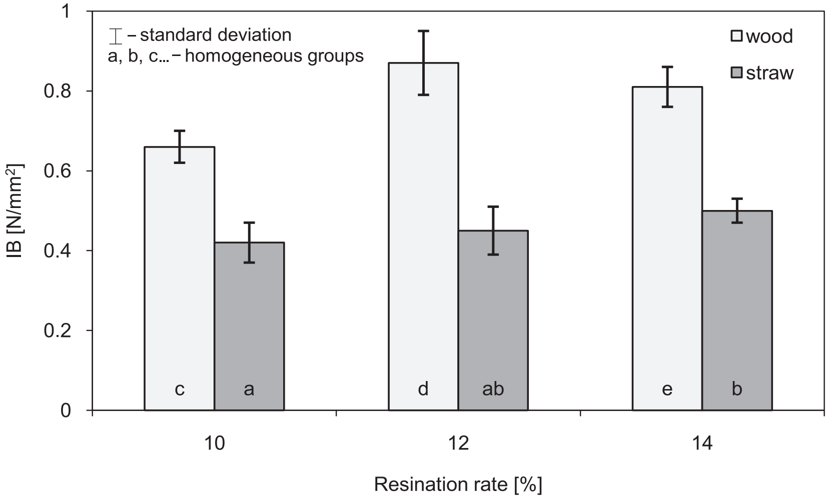

Fig. 1. Internal bond of the experimental boards depending on resination rate of UF resin (density of boards 700 kg/m^3)

The values obtained for the straw boards, even for the maximum resination rate of 14%, were still lower than for the wood particleboards with 10% gluing. The data presented in fig. 1 show that an increase in the resination rate more strongly influenced the internal bond of the straw boards than the wood particleboards. No improvement in the internal bond of the straw particleboard for the resination rate exceeding 12% was probably due to the fact that this resin content was optimal, and its increase caused no further improvement in this respect. The reduced IB of the particleboard, visible on the graph and associated with increasing the resination rate from 12% to 14%, was due to a scattering of the results around the mean IB values that, after allowing for standard deviations, were between 0.77 and 0.97 N/mm^2 for the 12% resination rate and 0.70 and 0.89 for the 14% resination rate. Despite this, the tested boards met the requirements for both P1 and P2 boards, regardless of the type of raw material (for the boards type P1 and P2 with a thickness of 6–13 mm the required values were 0.29 and 0.40 N/mm^2, respectively). For these types of boards, the EN 312 standard only includes requirements concerning the modulus of rigidity and internal bond. However, to provide a full specification of the produced experimental boards, their water resistance was determined by measuring their swelling and water absorption following a 24 hour period of soaking in water. Data from table 2 indicate that a higher resination rate in the boards containing straw particles improved their water resistance to a much greater degree than in the boards made of wood particles. In the straw boards with 14% resination rate, swelling and water absorption were reduced to a level comparable to the parameters of the wood particleboards with 12% resination rate (homogeneous group ”a”). The values of swelling and water absorption were different due to the lack of outer layers, which normally effectively block water penetration inside the board. Therefore, it may be concluded that using a 10% resination rate with UF resin ensures the manufacture of P1 and P2 boards made of mustard straw particles with the required strength. Taking this into account, further experiments were focused on the possibility of reducing the density of the boards made exclusively of straw particles, glued with a 10% resination rate of the UF resin. The results of the tests are shown in table 3 and in fig. 2. Based on the tests, it was concluded that lowering the density of the straw boards down to 500 kg/m^3 reduced the internal bond perpendicular to the board plane to a value of 0.17 N/mm^2. Thus, these boards did not meet the requirements of the EN 312 standard, even for P1 boards. On the other hand, the straw boards with a density of 600 kg/m^3 had a internal bond of 0.35 N/mm^2, thus it is possible to reduce the density of mustard straw boards and to use them for general purposes in dry conditions (boards of P1 type).

Table 3. Properties of the experimental boards depending on their density

Density	Kind of particles	MOR	MOE	TS	WA
[kg/m^3]		[N/mm^2]		[%]	
500	wood	5.98 (1.21) a	1270 (218) a	28.9 (2.73) b	117.1 (10.3) b
600		10.1 (1.29) b	2160 (237) d	30.4 (2.74) b	103.9 (3.54) a
700		12.8(1.38)* c	2750 (225) b	51.0 (4.56) a	104.6 (11.0) a
500	straw	6.3 (0.66) a	1260 (83.0) a	53.1 (3.37) a	158.1 (5.26) d
600		10.4 (1.13) b	1680 (141) c	52.9 (5.05) a	141.8 (16.7) c
700		16.0 (1.11) d	2980 (180) b	62.1 (2.35) c	113.8 (8.99) ab

Legenda as in table 2; resination rate of particleboards Z = 10%

Lowering the density of the straw boards also resulted in a lower bending strength, although the obtained values were comparable to the parameters of the wood particleboards with the same density (homogeneous groups ”b”). However, it is worth mentioning that the wood particleboards showed a smaller downward trend in this respect than the straw boards, as compared to the boards with a density of 700 kg/m^3. The modulus of rigidity for the wood particleboards with a density of 600 and 500 kg/m^3 was 22% and 53% lower, while in the straw boards the corresponding decrease was 35% and 60%. Significant differences in the rigidity and water resistance of the straw and wood particleboards were also noticed. In comparison to the analogous wood particleboards, the straw boards were characterized by a 28% lower modulus of elasticity, and lower swelling and water absorption (by 74% and 36%, respectively).

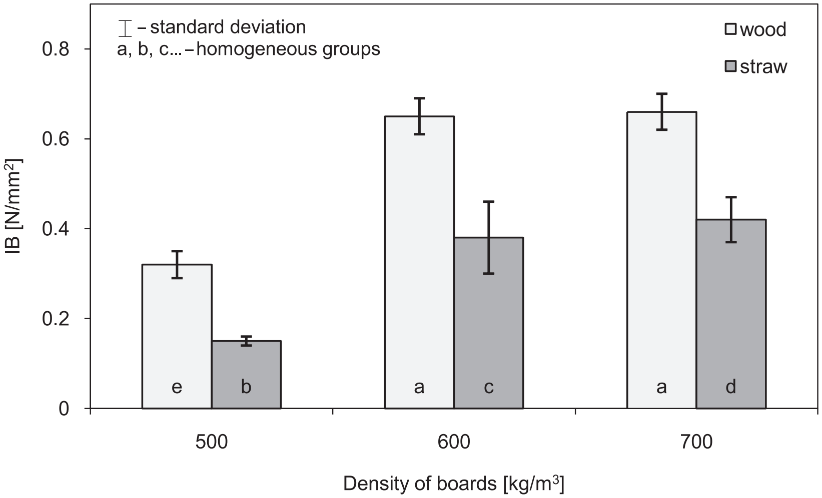

Fig. 2. Internal bond of the experimental boards depending on their density (resination rate of boards Z = 10%)

The results of the studies on the possibility of using mustard straw as a sub--stitute for wood particles in the manufacture of particleboards glued with UF resin were similar to those obtained for different types of raw materials, such as cereal straw or alternative crops e.g. rape or evening primrose, tested previously [Dziurka et al. 2005; Dukarska et al. 2006; Dukarska et al. 2012]. The evaluation of the mustard straw particleboards was considerably affected by the fact that they were single-layer boards, without any outer layers that determine to a large extent the values of the modulus of rigidity and modulus of elasticity. The higher bending strength and stiffness of the boards were certainly due to their increased cohesiveness, resulting from the greater specific surface area and the slenderness of the straw particles. The greater specific area of the straw particles, as compared to the wood particles, meant that for the same resination rate, the surface of the adhesive joints was lower, and thus the board's internal bond was reduced. Furthermore, as shown by Dukarska et al. [2011], the degree of slenderness of the mustard straw particles was greater than of the wood particles, which positively influenced the board's modulus of rigidity, and had a negative effect on the internal bond. The lower values of the internal bond were also due to the poorer wettability of the straw particles, resulting from the significant content of wax substances and minerals in their surface layer. In addition, the less porous straw surface made the resin penetration more difficult. As a consequence, the bonds between the straw particles were weaker, and thus the internal bond of the straw board was lower. Therefore, it is clear that the increased resination rate of the straw particles improved the mechanical properties of the boards due to the formation of more abundant adhesive joints on their surface. Apart from the structure, the amount and the type of binder, one of the main factors determining the physical and mechanical properties of particleboards is the density. Increased density results in an improvement in all the mechanical properties, due to the greater compression of the boards, accompanied by the greater contact surface of the lignocellulosic material particles. Thus, according to expectations, lowering the board density in the study caused a drop in their strength, thereby limiting their use as P1 boards.

The tests of the hygienic parameters of the experimental boards, based on the free formaldehyde content, showed an increasing content of formaldehyde with an increasing resination rate with the UF resin. Regardless of the type of raw material, these changes did not significantly affect the hygienic parameters of the boards, as evidenced by the perforator values ranging within 3.6–4.8 mg CH_2O/100 g of dry mass, obtained for the 14% resination rate. Therefore, the investigated boards can be classified as E1 hygiene class.

The VOC emissions were determined for the boards with a 10% resination rate and densities of 700 and 600 kg/m^3. The results recorded for the volatiles are presented in table 4. The concentrations of organic volatiles released by the tested boards ranged from 145 to 378 µg/m^3. The amounts of volatiles released into the air by the boards manufactured from mustard at 262 up to 378 µg/m^3 were greater than by the boards produced from the pine particles, for which they ranged from 145 to 207 µg/m^3. The spectrum of compounds released by the tested types of boards varied slightly. All the boards released toluene, α-pinene, hexanal and benzaldehyde. Toluene was released in the greatest amounts. The straw boards emitted from 200.6 to 223.9 µg/m^3 of toluene, while the boards made from pine wood released its smaller amounts ranging from 88.9 to 95.1 µg/m^3. The boards made of mustard also released slightly greater amounts of α-pinene. The concentration of hexanal fell within a similar range of 28.8 to 37.2 µg/m^3. As shown in literature reports [Salthammer et al. 1999; Uhde, Salthammer 2007], the presence of aldehyde compounds may be caused by the degradation reactions of the fatty acids contained in the wood. Hexanal is a typical degradation product of linolic acid. In turn, the concentration of benzaldehyde ranged from 7.5 to 40.4 µg/m^3.

Table 4. Concentrations of VOC from experimental boards [µg/m^3]

Compound	Kind of particles			
	wood		straw	
	density [kg/m^3]			
	700	600	700	600
2-propanol	–	–	57.8	–
Toluene	95.1	88.9	223.9	200.6
Hexanal	28.8	30.0	37.2	29.5
Phenylethyne	26.5	–	–	–
α-pinene	9.4	9.6	28.8	11.6
Benzaldehyde	40.4	7.5	9.6	7.7
Unidentified	6.6	9.1	21.1	12.9
TVOC	207	145	378	262

The greatest amounts of this compound were emitted by the particleboards with a density of 700 kg/m^3. The straw boards with the same density also emitted relativelyhigh amounts of 2-propanol, which was not recorded in the case of the other boards, while the boards produced from pine wood were a source of phenylethylene emissions. A reduction of the board density to 600 kg/m^3 caused a reduction in TVOC emissions. As shown in literature data, the concentration of volatile organic compounds emitted from wood-based materials may change within a very wide range of values. Brown [1999] reported that VOC emissions from particleboard resinated with melamine-urea-formaldehyde resin after 24 h exposure amounted to 160 µg/m^3. Analyses conducted by Stachowiak-Wencek et al. [2011] on particleboards produced under commercial conditions showed that emissions ranged from 459 to 3477 µg/m^3. Levels of VOC emissions from wood-based materials recorded by Kowaluk et al. [2011] were not high. Boards manufactured from fibrous particles released volatile substances at 50–431 mg/m^3, while boards produced from typical commercial particles emitted 117 mg/m^3. In turn, Jensen et al. [2001] presented aldehyde emissions from wood-based materials. The highest emission of aldehydes among the tested wood-based materials was recorded for OSB resinated with phenolic resin at approx. 530 µg/m^{2}h, while it was the lowest one from MDF resinated with urea-formaldehyde adhesive, amounting to approx. 130 µg/m^{2}h. Among the tested particleboards, the greatest amounts of aldehydes, approx. 300 µg/m^{2}h, were emitted by the boards resinated with polyurethane adhesive. The emission of aldehydes from the particleboards manufactured using urea-formaldehyde and melamine-urea-phenolic resin was lower, amounting to 200 and 180 µg/m^{2}h, respectively.

Considering the use of such boards for general purposes and interior decoration in a dry environment, the possibilities of post-production waste disposal through incineration or co-incineration were also investigated. The process of the thermal decomposition of the mustard straw particleboards was compared with that of wood particleboard based on thermogravimetric analysis. The obtained thermograms were used to determine the thermal performance (table 5) of the experimental boards made of wood and mustard straw particles. The registered DTG curves made it possible to determine: the initial thermal decomposition temperature (T_i), the temperature of the maximum weight loss rate (T_{max}), the final thermal decomposition temperature (T_f), the weight loss at the above-mentioned temperatures (W_{Ti}, W_{Tmax}, W_{Tf}) and the total weight loss (W_T). In addition, the weight loss at up to 120°C was determined (W_{120}; related to the sample water content) and at 200°C (W_{200}; pressing temperature of the experimental boards). The thermograms (DTG curve) displayed two peaks (figs 3 and 4). The first peak covered the temperature range from approximately 40–43°C to 120°C and was associated with the loss of water contained in the sample. The weight loss determined for this temperature range was approximately 7% (table 5). The second peak visible on the thermograms was associated with the thermal decomposition of the samples. The DTG curves recorded for the experimental boards indicated that the thermal decomposition of the samples was triggered after exceeding the temperature (T_i) of 183°C for the pine particleboards and 173°C for the straw boards. The weight loss calculated for T_i of the studied material was similar and amounted to approximately 10%. Pyrolysis of the experimental particleboard proceeded at a maximum rate of (T_{max}) 336°C. The value of T_{max} determined for the straw board was 308°C. At the maximum degradation rate, the pine particleboard lost (W_{Tmax}) about 54% of its initial weight, and for the straw board this value was 44%. It was observed that the dynamics of the thermal decomposition process of the experimental boards was reduced at similar temperatures (T_f).

Table 5. Thermal characteristic of the experimental boards

Parameter	Units	Kind of particles	
		wood	straw
T_i	[°C]	183	173
W_{Ti}	[%]	10.72	10.44
T_{max}	[°C]	336	308
W_{Tmax}	[%]	54.24	44.23
T_f	[°C]	379	377
W_{Tf}	[%]	68.24	65.53
W_T	[%]	85.35	84.38
W_{120}	[%]	7.81	7.74
W_{200}	[%]	11.11	11.31

T_i – initial thermal decomposition temperature, W_{Ti} – weight loss at the initial thermal decomposition temperature, T_{max} – temperature of maximum weight loss rate, W_{Tmax} – weight loss at the temperature of maximum weight loss rate, T_f – final thermal decomposition temperature, W_{Tf} – weight loss at the final thermal decomposition, W_T – total weight loss, W_{120} – weight loss at 120°C, W_{200} – weight loss at 200°C

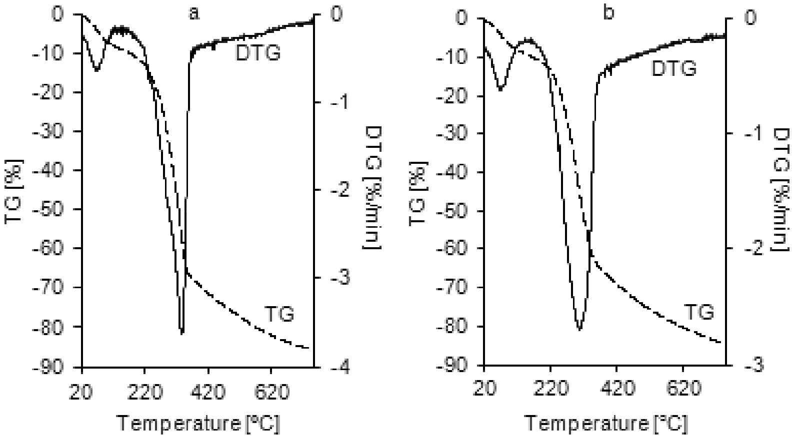

Fig. 3. Thermogram for experimental boards made from: a) wood particles b) straw particles

The value of T_f for the wood particleboard was 379°C and it amounted to 377°C for the board made of straw. Until it reached the final temperature of thermal decomposition, the wood particleboard degradation degree was about 68%. The weight loss at the final temperature of active thermal decomposition, observed for the straw particleboard, was approximately 65%. A thermogravimetric analysis was conducted to a final temperature of 750°C, when the total weight loss due to the thermal decomposition of the experimental boards was determined. As a result of the thermal decomposition at a temperature of up to 750°C, the boards made of the pine particles and mustard straw lost 85.35% and 84.38% of their initial mass, respectively. The thermal performance analysis of the studied boards was supplemented by determining their weight loss at the pressing temperature, i.e. at 200°C. At this temperature, the experimental boards lost about 11% of their initial weight.

The thermogram analysis revealed a variable thermal performance of the studied materials. The samples of the experimental boards varied in their initial pyrolysis temperature (T_i) and the temperature of the maximum decomposition rate (T_{max}). Differences in the thermal performance of the studied boards can be explained by using different raw materials for their manufacture. These raw materials, despite both being lignocellulosic materials, differ in the content of structural and nonstructural components [Dziurka et al. 2005]. Literature data show that the main components of lignocellulosic materials (cellulose, hemicellulose, and lignin) undergo thermal degradation at various temperatures [Hill 2006]. Research has shown that the thermal decomposition temperature of the cellulose amorphous regions were lower than in the crystalline regions [Kim et al. 2001]. This also indicated the lower thermal stability of hemicelluloses than cellulose [Fengel, Wegener 1989]. Lignin is the most heat-resistant structural component of lignocellulosic materials, but its thermolysis may begin at relatively low temperatures as evidenced by the appearance of various phenolic compounds among the degradation products [Yoshida et al. 1987].

Conclusion

In summary, it can be concluded that white mustard straw is a valuable substitute for wood in general purpose particleboards, intended for interior design and furniture, i.e. P1 and P2 boards. A ten percent resination rate is necessary to achieve the required mechanical properties. In addition, such an amount of UF resin enables the manufacture of low density P1 boards, made of straw, with a density reduced to 600 kg/m^3, which further contributes to lowering production and transportation costs.

VOC emission tests revealed that higher amounts of volatile substances were emitted by the boards made of mustard straw (from 262 to 378 mg/m^3) than ones made of wood (from 145 to 207 mg/m^3). The spectrum of the identified compounds was only slightly different.

The comparison of thermal performance of the studied boards revealed the higher thermal resistance (T_i values) of wood particleboard than white mustard straw particleboard. It was found that the dynamics of the thermal decomposition process in the experimental boards were reduced at similar temperatures. The degradation degree (W_T) of both experimental boards was similar at the final pyrolysis temperature.

References

Azizi K., Tabarsa T., Ashori A. [2011]: Performance characterizations of particleboards made with wheat straw and waste veneer splinters. Composites: Part B 42 [7]: 2085–2089

Bekhta P., Korkut S., Hiziroglu S. [2013]: Effect of pretreatment of raw material on properties of particleboard panels made from wheat straw. Bioresources 8 [3]: 4766–4774

Boquillon N., Elbez G., Schönfeld U. [2004]: Properties of wheat straw particleboards bonded with different types of resin. Journal of Wood Science 50 [3]: 230–235

Brown S.K. [1999]: Chamber assessment of formaldehyde and VOC emissions from wood-based panels. Indoor Air 9 [3]: 209–215

Czarnecki R., Dukarska D. [2010]: Estimating the possibilities of applying *Sida Hermaphrodita Rusby* to the production of low-density particleboards. Annals of Warsaw University of Life Science – SGGW, Forest and Wood Technology 71: 83–86

Dukarska D., Dziurka D., Łęcka **J., Mirski R.** [2006]: The effect of amounts of rape straw added to chips on properties of particle boards depending on the type of bonding agent. Electronic Journal of Polish Agricultural Universities (EJPAU) 9 [3]: #12

Dukarska D., Łęcka **J., Czarnecki R.** [2012]: The effect of wood chip substitution with evening primrose waste on properties of particleboards depending on the type of binding agent. Electronic Journal of Polish Agricultural Universities (EJPAU) 15 [2]: #05

Dukarska D., Łęcka **J., Szafoni K.** [2011]: Straw of white mustard (*Sinapis Alba*) as an alternative raw material in the production of particle boards resinated with UF resin. Acta Scientiarum Polonorum, Silvarum Colendarum Ratio et Industria Lignaria [10]: 21–28

Dziurka D., Mirski R., Łęcka **J.** [2005]: Properties of boards manufactured from rape straw depending on the type of the binding agent. Electronic Journal of Polish Agricultural Universities (EJPAU) 8[3]: #0

Dziurka D., Mirski R., Łęcka **J.** [2010]: Rape straw as a substitute of chips in core layers of particleboards resinated with PMDI. Electronic Journal of Polish Agricultural Universities (EJPAU) 13[4]: #06

FAO STAT [2012]: http://faostat.fao.org [accessed: 08.05.2014]

Fengel D., Wegener G. [1989]: Wood chemistry, ultrastructure, reactions. Walter de Gruyter, Berlin New York

Guler C., Ozen R. [2004]: Some properties of particleboards made from cotton stalks (*Gossypium hirsitum L.*). Holz Roh- und Werkstoff 62 [1]: 40–43

Hill C.A.S. [2006]: Wood modification: chemical, thermal and other processes. Wiley series in renewable resources, Wiley and Sons Eds Chichester Sussex UK

Jensena L.K., Larsenb A., Mlhavec L., Hansend M.K., Knudsene B. [2001]: Health evaluation of volatile organic compound (VOC) emissions from wood and wood-based materials. Archives of Environmental Health: An International Journal 56 [5]: 419–432

Kim D.Y., Nishiyama Y., Wada M., Kuga S., Okano T. [2001]: Thermal decomposition of cellulose crystallites in wood. Holzforschung 55 [5]: 521–524

Kowaluk G., Komorowicz M., Witczak M., Fuczek D. [2011]: Formaldehyde content in and VOC release from particleboards made of fibrous chips. Drewno. 54 [185]: 81–88

Li X.J., Cai Z.Y., Winandy J.E., Basta A.H. [2011]: Effect of oxalic acid and steam pretreatment on the primary properties of UF-bonded rice straw particleboards. Industrial Crops and Products 33 [3]: 665–669

Nemli G. [2003]: Effects of some manufacturing factors on the properties of particleboard manufactured from Alder (*Alnus glutinosa subsp. Barbata*). Turkish Journal of Agriculture and Forestry 27 [2]: 99–104

Park H.J., Oh S.W., Wen M.Y. [2012]: Manufacture and properties of miscanthus-wood particle composite boards. Journal of Wood Science 58 [5]: 459–464

Piętka T. [2007]: Postępy w badaniach nad genetyką i hodowlą roślin oleistych z rodzaju Brassica (z wyłączeniem Brassica napus L.). Rośliny Oleiste-Oilseed Crops XXVIII 1: 75–84

Salthammer T., Schwarz A., Fuhrmann F. [1999]: Emissions of reactive compounds and secondary products from wood-based furniture coatings. Atmospheric Environment 33: 75–84

Sawicka B., Kotiuk E. [2007]: Gorczyce jako rośliny wielofunkcyjne. Acta Scientiarum Polonorum Agricultura 6 [2]: 17–27

Stachowiak-Wencek A., Prądzyński W., Krzywosińska P. [2011]: Investigations on volatile organic compounds (VOC) emissions from wood-based materials. Annals of Warsaw University of Life Science – SGGW, Forest and Wood Technology 76: 59–63

Suleimenov M., Akhmetov K., Kaskarbayev Z., Kireyev A., Martynova L., Medeubayev R. [2005]: Role of wheat in diversified cropping systems in dryland agriculture of central Asia. Turkish Journal of Agriculture and Forestry 29 [2]: 143–150

Uhde E., Salthammer T. [2007]: Impact of reaction products from building materials and furnishings on indoor air quality – A review of recent advances in indoor chemistry. Atmospheric Environment 41: 3111–3128

Yoshida H., Mörck R., Kringstad K.P. [1987]: Fractionation of kraft lignin by successive extraction with organic solvents. II. Thermal properties of kraft lignin fractions. Holzforschung 41 [3]: 171–176

List of standards

EN 120:1992 Wood based panels. Determination of formaldehyde content – extraction method called the perforator method
EN 310:1993 Wood based panels. Determination of modulus of elasticity in bending and of bending strength
EN 312:2005 Particleboards – specifications
EN 317:1993 Particleboards and fiberboards. Determination of swelling in thickness after immersion in water
EN 319:1993 Determination of tensile strength perpendicular to the plane of the board

Acknowledgements

We would like to express our gratitude to Łukasz Nędza MSc for his help and support in implementing this research project.