Improving Properties of Particleboards with Reduced Density

Karoly Lengyel,[a] Marius Catalin Barbu,[b] Mihaela Campean,[b,*] Nicolae Badin, [a] and Bogdan Bedelean [b]

The goal of this research was to examine factors affecting the feasibility of manufacturing particleboards at significantly lower density, while reducing the formaldehyde emissions. A further goal was to not significantly affect other important physical and mechanical properties of the boards, including swelling in thickness, surface absorption, bending strength, modulus of elasticity, internal bond, and surface soundness. By varying the raw material recipe (ratio between hardwood and softwood chips), it was found that increasing the amount of hardwood chips led to a significant decrease of the formaldehyde emissions, but also to a significant increase of the thickness swelling and surface absorption. The simple density reduction of particleboards was not a viable alternative because all properties were seriously affected. Therefore, the tests on particleboards with reduced density were repeated, but this time an isocyanate-based additive was added into the recipe at 0.25% and 0.4%. A noticeable improvement of all analyzed properties was achieved.

Keywords: Particleboards with lower density and reduced formaldehyde emission; Influence on bending strength; Modulus of elasticity; Internal bond

Contact information: a: Kastamonu Romania, Ierbus Str. 37, 545300 Reghin, Romania; b: Transilvania University of Brasov, Faculty of Wood Engineering, Universitatii Str. 1, 500036 Brasov, Romania;
** Corresponding author: campean@unitbv.ro*

INTRODUCTION

The present trend in the particleboard industry is to produce boards with the lowest possible density and with reduced formaldehyde emissions while still meeting all existing quality standards. Production of the boards should not increase the production costs due to the requirements of other additives nor lower the productivity, in order to maintain the price-advantage of particleboards in the competition with other wood-based panels.

Different weight-saving techniques include using lightweight wood species such as poplar (Akrami *et al.* 2014) or bamboo (Malanit *et al.* 2010) or combining wood chips and agricultural fibers such as cotton (Güler *et al.* 2001), sunflower stalks (Bektas *et al.* 2005), kenaf (Kalaycıoğlu and Nemli 2006), and rice straw (Akyldiz *et al.* 2015). Other options are increased resination (Monteiro *et al.* 2016) and optimized board density profiles (Poppensieker and Thömen 2005; Lüdtke *et al.* 2007). These are only four of the directions followed in this field of research. Each technique also has its disadvantages: either the production of lightweight panels is too laborious (involving excessive costs), the mechanical and physical performances of the panels are significantly decreased, or connectors for later assembly are too complicated (Barbu 2015). Thus, a cost-effective solution for producing particleboards with reduced density and lower formaldehyde emission that meet the standard physical and mechanical requirements (EN 312 2010) remains a challenge.

The main objective of this research was to test different composition recipes of particleboards by varying the density of the boards, the ratio of hardwood/softwood chips, and the additive amount. The final outcome was to find the optimum composition allowing the simultaneous reduction of the density and of the formaldehyde emission of the boards, without affecting other important physical and mechanical properties, such as the swelling in thickness, surface absorption, bending strength, modulus of elasticity in bending, internal bond, and surface soundness.

EXPERIMENTAL

Materials, Methods, and Equipment

Three-layered raw particleboards (type P2) with a thickness of 28 mm were produced on an industrial line at Kastamonu Romania (Reghin, Romania) by using an urea-formaldehyde (UF) adhesive based on formaldehyde, urea (at a molar ratio F/U=0.96) and water (36%). Urea-formaldehyde resins are the most important type of adhesive resins for the production of wood-based panels. They provide high reactivity and good performance in the production, and their price is relatively low (Dunky 1998).

First, particleboards with the usual density (ρ = 625 kg/m^3) were tested; then particleboards with the density reduced by 7% were tested. The reduction value (7%) was established by the authors taking as reference two limiting values: a density reduction by more than 5% was envisaged, in order to obtain relevant results; the density reduction had to be restricted at less than 10% in order to still comply with the quality parameters, considering that these panels were produced in a continuous production system.

Table 1. Composition of the 28 mm Thick Particleboards

Ref. No.	Ratio of Hardwood/Softwood Chips	Isocyanate Additive (%)	Resin (%)		Urea (%)		Hardener (%)	
			CL	SL	CL	SL	CL	SL
Particleboards with normal density (ρ = 625 kg/m^3)								
1	25/75	no additive	8.0	11.0	0.00	0.17	0.22	0.18
2	30/70	no additive	8.0	11.0	0.00	0.17	0.22	0.15
3	35/65	no additive	8.0	11.0	0.00	0.17	0.22	0.20
Particleboards with reduced density (ρ = 580 kg/m^3)								
4	25/75	no additive	8.0	11.0	0.00	0.17	0.22	0.18
5	30/70	no additive	8.0	11.0	0.00	0.17	0.22	0.18
6	35/65	no additive	8.0	11.0	0.00	0.17	0.22	0.18
7	25/75	0.25	8.0	11.0	0.00	0.17	0.18	0.22
8	30/70	0.25	8.0	11.0	0.00	0.17	0.18	0.22
9	35/65	0.25	8.0	11.0	0.00	0.17	0.18	0.22
10	25/75	0.4	8.0	11.0	0.00	0.17	0.22	0.18
11	30/70	0.4	8.0	11.0	0.00	0.17	0.22	0.18
12	35/65	0.4	8.0	11.0	0.00	0.17	0.18	0.22

CL = core layer; SL = surface layer

These two tests (with usual and low density particleboards) were called "base tests" because the boards contained no additive and thus served as references. The third set of tests was meant to improve the properties of the boards with reduced density by using an isocyanate additive into the UF adhesive recipe. Two amounts of additive were tested:

0.25% and 0.4%. Furthermore, the ratio of hardwood/softwood chips within the raw material was varied, resulting in 12 combinations (Table 1). A total of 200 particleboards from each recipe were produced on an industrial line, out of which 10 boards were selected for each test.

As one may notice, the formaldehyde resin and urea amounts were maintained constant for all recipes, but, the hardener amount was varied in order to maintain the same reactivity (gelation time) of the resin. This was necessary considering that each recipe took a production time of at least 10 h, the manufacturing of all boards being unfolded during several weeks.

The same pressing parameters were applied, in all trials, as follows: press speed 230 mm/s; pressing factor 5.95 s/mm; maximum pressing temperature 245 °C; and maximum pressure 3.12 N/mm^2.

After pressing, the boards were cooled for 30 min at ambient temperature and 65% RH. Then, specific test pieces were cut from ten randomly selected boards, according to EN 326-1 (1994), in order to determine the most relevant physical and mechanical properties.

Density

The particleboard density was determined according to EN 323 (1993). Twenty samples from each recipe, sized at 50 mm × 50 mm × 28 mm, were first weighed at an accuracy of 0.01g and then measured at an accuracy of 0.1 mm. The thickness (t) was measured in the central point by a micrometer, and the dimensions b_1 and b_2 were measured at mid width and length by a sliding gauge.

The density of each test piece was then calculated according to Eq. 1,

$$\rho = \frac{m}{b_1 \cdot b_2 \cdot t} \cdot 10^6 [kg/m^3] \quad (1)$$

where m is the sample mass (g), b_1 and b_2 are the sample dimensions (mm), and t is the sample thickness (mm).

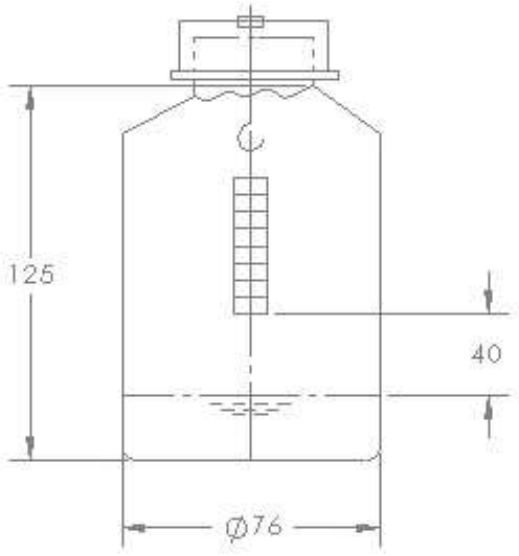

Fig. 1. Principle of determining the formaldehyde emission from particleboards by means of the flask method (EN 717-3 1996)

Formaldehyde Emissions

The formaldehyde emissions were determined using the flask method (EN 717-3 1996). Twelve test pieces from each recipe were used to determine the moisture content according to EN 322 (1993). Another 12 test pieces from each recipe, sized at 25 mm × 25 mm × 28 mm, were weighed. The samples were then attached to a hook on the inner side of the lid of a glass container, so that the sample was suspended above a bath of 50 mL distilled water (Fig. 1). Two glass containers were used, for six replicates each. The bottles were closed completely airtight and maintained at a constant temperature 40 ± 1 °C for 180 ± 1 min in a Lange LT200 thermoreactor (Manchester, UK) (Fig. 2). During this time, the formaldehyde released by the particleboard samples was absorbed into the water. The formaldehyde content of the water was determined photometrically by the acetyl-acetone method. Briefly, 50 mL of solution from each glass container was transferred immediately after the 180 ± 1 min into two 50 mL flasks and cooled at an ambient temperature to 20 °C. A total of 10 mL were added to 10 mL of acetyl-acetone solution and 10 mL ammonium acetate solution in a 50 mL flask. The flask was stoppered, shaken, and warmed for 15 min in a water bath at 40 ± 1 °C. The formaldehyde concentration was determined with a Lasa 30 spectrophotometer (Manchester, UK) (Fig. 2) and calculated according to Eq. 2,

$$F_v = \frac{(A_S - A_B) \cdot f \cdot 50 \cdot 10 \cdot (100 + H)}{m} \left[\frac{mg}{kg}\right] \quad (2)$$

where A_s is the absorbance of the solution from the glass bottle, A_B is the absorbance of distilled water, f is the slope of the calibration curve (mg/mL), H is the moisture content of the test piece (%), and m is the mass of the test piece (g).

Fig. 2. Equipment to measure formaldehyde emission photometrically by the acetyl-acetone method

Swelling in Thickness after Water Immersion

The swelling in thickness after water immersion was determined according to EN 317 (1993). Eight samples from each recipe, sized at 50 mm × 50 mm × 28 mm, were first measured in thickness (at the intersection of diagonals) by a micrometer with an accuracy of 0.01 mm. The samples were vertically immersed for 2 h in a clean, still, thermostatically

controlled water bath at pH 7 ± 1 and 20 ± 1 °C (NUVE-BS402, Ankara, Turkey; Fig. 3). During the test, the specimens were separated from each other and from the bottom and the sides of the water bath. The specimens were immersed so that their upper edges were covered by 25 ± 5 mm of water throughout the test. The water was changed after each test.

After 2 h of immersion, the test pieces were taken out of the water, and after removing the excess water, the thickness of each test piece was measured again. The swelling in thickness (G_t) was expressed according to the following formula,

$$G_t = \frac{t_2 - t_1}{t_1} \cdot 100[\%] \quad (3)$$

where t_2 is the test piece thickness after immersion (mm) and t_1 is the test piece thickness before immersion (mm).

Fig. 3. Equipment used to determine the swelling in thickness after water immersion

Surface Absorption

The surface absorption was determined according to EN 382-1 (1993). Eight samples from each recipe, sized at 300 ± 2 mm × 300 ± 2 mm × 28 mm, were placed on a 60 ± 5° inclined support (Fig. 4).

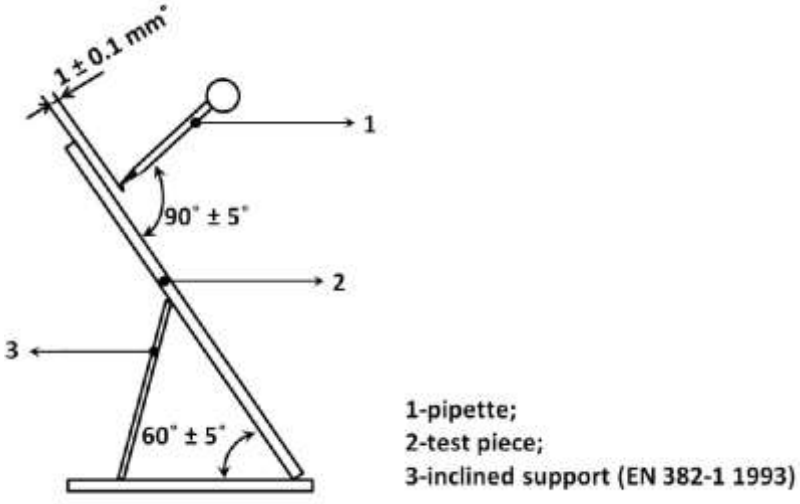

Fig. 4. Experimental set-up for the determination of the surface absorption: 1-pipette; 2-test piece; 3-inclined support (EN 382-1 1993)

The pipette for dropping the toluene solution was placed at a distance of 1 ± 0.1 mm, perpendicular to the panel surface. Next, 1 mL of toluene was dropped at regular time intervals of 4 s and left to flow on the panel surface. The maximum length of the trace was measured along a line parallel to the test piece margins, at an accuracy of ± 1 mm. The operation was repeated on the other panel face as well. The surface absorption (A_s) was then calculated as the arithmetic mean of the two measured values, in mm.

Bending Strength and Modulus of Elasticity in Bending

The bending strength and modulus of elasticity in bending were determined according to EN 310 (1993). Six samples from each recipe, sized at (20t + 50) mm × 50 mm × panel thickness (t), were tested by IMAL IB600 equipment (San Damaso, Italy) (Fig. 5).

The distance between the centers of the supports was adjusted at 20 times the nominal thickness of the panel. The test piece was placed flat on the supports, with its longitudinal axis at right angles to those of the supports with the center point under the load. The load was applied at a constant rate of the cross-head movement throughout the test. The rate of loading was adjusted so that the maximum load was reached within 60 ± 30 s. The deflection in the middle of the test piece (below the loading head) was measured to an accuracy of 0.1 mm. These values were plotted against the corresponding loads measured to an accuracy of 1% of the measured value. The maximum load was recorded to an accuracy of 1% of the measured value.

Fig. 5. Equipment used to determine the bending strength and modulus elasticity in bending

The bending strength of each test piece (f_m) was calculated by Eq. 4,

$$f_m = \frac{3 \cdot F_{max} \cdot l_1}{2 \cdot b \cdot t^2} [N / mm^2] \quad (4)$$

where F_{max} is the maximum load (N), l_1 is the distance between the centers of the supports (mm), b is the test piece width (mm), and t is the test piece thickness (mm).

The modulus of elasticity in bending (E_m) was calculated according to Eq. 5,

$$E_m = \frac{l_1^2 \cdot (F_2 - F_1)}{4 \cdot b \cdot t^2 \cdot (a_2 - a_1)} [N/mm^2] \quad (5)$$

where ($F_2 - F_1$) is the increment of load on the straight line portion of the load-deflection curve and ($a_2 - a_1$) is deflection increment at the mid length of the test piece corresponding to ($F_2 - F_1$).

Tensile Strength Perpendicular to the Plane of the Board (Internal Bond)

The tensile strength perpendicular to the plane of the board, also called the internal bond, was determined according to EN 319 (1993). Eight samples from each recipe, sized at 50 mm × 50 mm × 28 mm, were tested by means of the IMAL IB600 equipment (San Damaso, Italy) (Fig. 5). Each test piece was loaded with a tension force uniformly distributed perpendicular as follows,

$$f_{t1} = \frac{F_{max}}{a \cdot b} [N/mm^2] \quad (6)$$

where F_{max} is the maximum force (N), and a and b are the test piece length and width, respectively (mm).

Surface Soundness

The surface soundness was determined according to EN 311 (2002). Eight samples from each recipe, sized at 50 mm × 50 mm × panel thickness, were tested by the same IMAL IB600 equipment (San Damaso, Italy) (Fig. 5). A steel mushroom-shaped pad with a diameter of 35.6 ± 0.1 mm was glued with hot-melt adhesive on the sample surface. A circular groove was cut at 0.3 mm depth through the coating-material so that it just broke through into the underlying board. The surface soundness (*SS*) was calculated from the tensile load required to pull off a defined surface area, as follows,

$$SS = \frac{F}{A} [N/mm^2] \quad (7)$$

where F is the maximum force recorded by the equipment (N) and A is the surface area delimited by the groove (1000 mm^2).

Statistical Analysis

One-way between-groups analysis of variance (ANOVA) was conducted to explore the influence of the hardwood/softwood chips ratio and of the P-MDI additive amount to improve the properties of particleboards.

RESULTS AND DISCUSSION

One-way between-groups analysis of variance (ANOVA) was conducted to explore the influence of hardwood/softwood chips ratio on normal and low density particleboards. The results are presented in Tables 2 and 3, respectively.

There was a statistically significant difference among the analyzed combinations in terms of all analyzed properties. Reducing the ratio of softwood chips (from 75% to 65%) in favor of the hardwood chips in particleboards with normal density produced the following results:

- density increased significantly, by 17.8%;
- formaldehyde emission decreased significantly, by 3.5%;
- swelling in thickness increased significantly, by 43.6%;
- surface absorption increased significantly, by 18.2% ;
- bending strength, modulus of elasticity, tensile strength, and surface soundness registered no significant changes.

Table 2. Influence of the Hardwood/Softwood Chips Ratio on Normal Density Particleboards

Raw Materials (%hardwood/ %softwood)	ρ (kg/m^3)	F_v, (mg/kg)	G_t, (%)	A_s (mm)	f_m (N/mm^2)	E_m (N/mm^2)	f_{t1} (N/mm^2)	SS (N/mm^2)
25/75	618.1^a (7.51)	729.7^a (4.2)	7.1 (1.24)	34.6^a (2.11)	11.1^a (0.32)	2434^a (29.45)	0.34^a (0.01)	1.08^a (0.11)
30/70	625.5^{ab} (8.08)	723.3^a (10.6)	9.1 ^{a} (0.73)	37.7^a (1.41)	10.6^a (1.00)	2209^a (255.51)	0.36^a (0.01)	1.05^a (0.03)
35/65	629.1^b (11.81)	703.7 (3.4)	10.2 ^{a} (1.57)	40.9 (3.58)	11.2^a (1.02)	2437^a (141.57)	0.36^a (0.03)	0.98^a (0.10)
F - value	5.42	21.30	13.03	12.09	0.92	3.57	1.88	2.77
Significance level	$p < 0.05$							
Effect size (Eta squared)	0.15	0.78	0.54	0.53	0.10	0.32	0.16	0.20

Note: Mean values are shown, with standard deviations in parentheses; Means followed by the same letter are not significantly different.

Based on the resulting eta squared (Table 2) and Cohen's classification, with 0.01 as a small effect, 0.06 as a medium effect and 0.14 as a large effect (Pallant 2007), it could be observed that most of the analyzed combinations had a large effect on the analyzed properties. The exception was in the case of the bending strength, where only a medium effect was revealed.

By analyzing all property modifications brought by the raw material participation in the particleboard recipe, the best variant was considered the one with lowest amount of hardwood chips (25/75), which was also the most cost-efficient recipe.

The effects of reducing by 7% the density of the particleboards upon the other physical and mechanical properties are presented in Table 3.

Table 3. Influence of the Raw Material Recipe (Hardwood / Softwood Chips Ratio) Upon the Properties of Particleboards With Reduced Density

Raw Materials (%hardwood/ %softwood)	ρ (kg/m^3)	F_v, (mg/kg)	G_t, (%)	A_s (mm)	f_m (N/mm^2)	E_m (N/mm^2)	f_{t1} (N/mm^2)	SS (N/mm^2)
25/75	589.8 (14.42)	1061.6 (31.4)	10.8 (0.46)	46.7 (3.36)	8.8 (0.45)	2252 (100.52)	0.23 (0.04)	1.00 (0.11)
30/70	589.8 (8.22)	959.8 (24.2)	14.3 (0.90)	75.0 (4.05)	9.1 (0.21)	2156 (357.15)	0.25 (0.02)	0.95 (0.10)
35/65	590.9 (7.44)	901.6 (19.3)	12.2 (0.81)	71.3 (4.16)	9.6 (0.71)	2215 (171.88)	0.24 (0.02)	0.99 (0.07)

Note: Mean values are shown, with standard deviations in parentheses

Reducing the density of the particleboards by 7% had negative influence on all properties of the particleboards: the formaldehyde emission, swelling in thickness, and surface absorption increased, and all mechanical properties decreased.

The one-way ANOVA test performed for the PB recipe with 25% hardwood chips and 75% softwood chips, revealed significant differences for all analyzed properties, excepting the surface soundness (Table 4).

Table 4. Influence of 7% Density Reduction Upon The Other Physical And Mechanical Properties of Particleboards

Type of particleboards	ρ (kg/m^3)	F_v, (mg/kg)	G_t, (%)	A_s (mm)	f_m (N/mm^2)	E_m (N/mm^2)	f_{t1} (N/mm^2)	SS (N/mm^2)
Normal density boards (25/75)	618.1 (7.51)	729.7 (4.2)	7.1^a (1.24)	34.6^a (2.11)	11.1^a (0.32)	2434 (29.45)	0.35 (0.02)	1.08^{abc} (0.11)
Low density boards (25/75)	589.8^a (14.42)	1061.6 (31.4)	10.8 (0.46)	46.7 (3.36)	8.8 (0.45)	2252^a (100.52)	0.23^a (0.04)	1.00^{ab} (0.11)

Note: Mean values are shown, with standard deviations in parentheses; Means followed by the same letter are not significantly different

Consequently, merely adjusting the particle type is not a viable alternative when the goal is to maintain properties at substantially decreased density. To improve the properties of the particleboards with reduced density, using an additive was absolutely necessary. A P-MDI (isocyanate) additive was added to the particleboards with reduced density, in two different amounts, namely 0.25% and 0.4%. The effects on the properties of the boards are presented in Tables 5 and 6, respectively.

Table 5. Influence of 0.25% P-MDI in Particleboards With Reduced Density

Raw Materials (%hardwood/ %softwood)	ρ (kg/m^3)	F_v, (mg/kg)	G_t, (%)	A_s (mm)	f_m (N/mm^2)	E_m (N/mm^2)	f_{t1} (N/mm^2)	SS (N/mm^2)
25/75	593.2 (10.66)	569.3 (27.9)	8.4 (0.38)	40.3 (2.16)	12.3 (0.77)	2186 (107.87)	0.26 (0.03)	1.19 (0.12)
30/70	597.0 (16.53)	495.0 (47.0)	7.3 (0.92)	35.0 (4.25)	11.6 (0.7)	2101 (87.24)	0.28 (0.03)	1.17 (0.09)
35/65	590.2 (11.11)	540.3 (34.7)	13.2 (1.79)	49.6 (5.68)	12.2 (0.89)	2396 (45.57)	0.29 (0.02)	1.06 (0.08)

Note: Mean values are shown, with standard deviations in parentheses

Table 6. Influence of 0.4% P-MDI in Particleboards With Reduced Density

Raw Materials (%hardwood/ %softwood)	ρ (kg/m^3)	F_v, (mg/kg)	G_t, (%)	A_s (mm)	f_m (N/mm^2)	E_m (N/mm^2)	f_{t1} (N/mm^2)	SS (N/mm^2)
25/75	592.4 (10.90)	512.4 (42.0)	7.9 (1.75)	38.0 (5.65)	11.7 (0.44)	2129 (47.79)	0.27 (0.02)	1.24 (0.12)
30/70	588.5 (12.92)	467.2 (35.8)	6.4 (0.79)	35.2 (3.29)	10.6 (0.51)	2138 (135.85)	0.29 (0.04)	1.05 (0.06)
35/65	594.6 (12.61)	431.9 (68.5)	11.6 (1.41)	50.3 (5.82)	12.3 (0.78)	2282 (38.46)	0.32 (0.03)	1.20 (0.11)

Note: Mean values are shown, with standard deviations in parentheses

One-way between-groups analysis of variance (ANOVA) was conducted to explore the efficiency of these alternatives in terms of improving the properties of particleboards with reduced density. The results obtained for the PB recipe with 25% hardwood chips and 75% softwood chips (Table 7), revealed that adding 0.25% P-MDI into the UF composition of particleboards with reduced density led to:

- significant decrease by 46.37% of the formaldehyde emission;
- significant decrease by 22.22% of the swelling in thickness;
- significant decrease by 13.70% of the surface absorption, and
- significant increase by 39.77% of the bending strength.

Table 7. Influence of P-MDI Additive Amount Upon The Properties of Particleboards With Reduced Density

Type of particleboards	ρ (kg/m^3)	F_v, (mg/kg)	G_t, (%)	A_s (mm)	f_m (N/mm^2)	E_m (N/mm^2)	f_{t1} (N/mm^2)	SS (N/mm^2)
Low density boards (25/75), with no additive	589.8^a (14.42)	1061.6 (31.4)	10.8 (0.46)	46.7 (3.36)	8.8 (0.45)	2252^a (100.52)	0.23^a (0.04)	1.00^{ab} (0.11)
Low density boards (25/75), with P-MDI 0.25%	593.2^a (10.66)	569.3 (27.9)	8.4^a (0.38)	40.3^b (2.16)	12.3^b (0.77)	2186^a (107.87)	0.26^{ab} (0.03)	1.19^{ac} (0.12)
Low density boards (25/75), with P-MDI 0.4%	592.4^a (10.90)	512.4 (42.0)	7.9^a (1.75)	38.0^{ab} (5.65)	11.7^{ab} (0.44)	2129^a (47.79)	0.27^b (0.02)	1.24^{ac} (0.11)

Note: Mean values are shown, with standard deviations in parentheses; Means followed by the same letter are not significantly different

By increasing up to 0.4% the amount of isocyanate in the recipe, only the formaldehyde emission registered a further significant decrease (by 10% compared to the recipe with 0.4% P-MDI and by 51.7% compared to recipe without additive). For all the other analyzed properties, the modifications were not significantly different.

The modification of each property for the recipe 25/75 (%hardwood/%softwood) for all four variants is presented in Figs. 6 through 12.

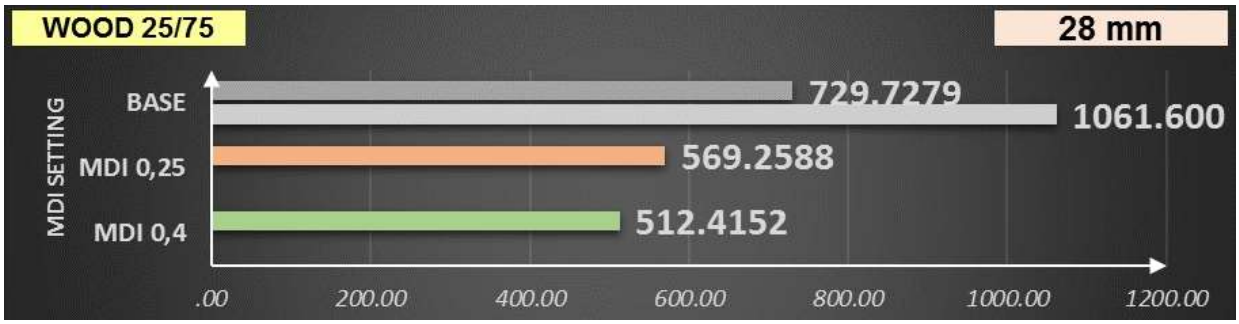

Fig. 6. Influence of board density and additive on the formaldehyde emission (flask method), in mg/kg.

In each figure, the dark grey bar represents normal density boards, without additive (base = reference). The light-grey bar indicates boards with reduced density, without additive (base = reference). The orange bar indicates boards with reduced density, with 0.25% additive, and the green bar represents boards with reduced density, with 0.4% additive.

Fig. 7. Influence of board density and additive on the swelling in thickness, in %

Fig. 8. Influence of board density and additive on the surface absorption, in mm

Fig. 9. Influence of board density and additive on the bending strength, in N/mm^2

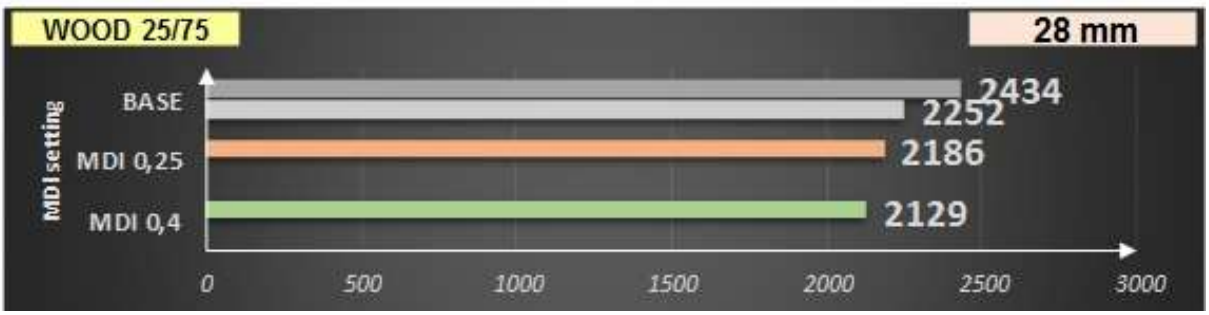

Fig. 10. Influence of board density and additive on the modulus of elasticity, in N/mm^2

Fig. 11. Influence of board density and additive on the internal bond, in N/mm^2

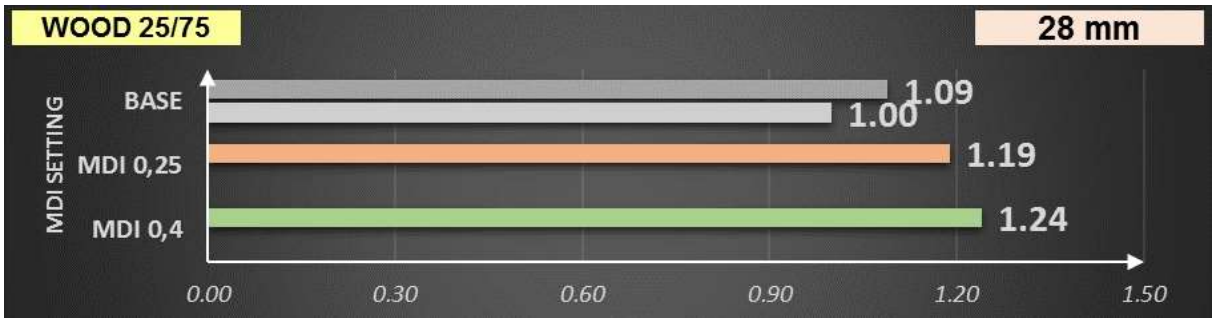

Fig. 12. Influence of board density and additive on the surface soundness, in N/mm^2

CONCLUSIONS

1. The ratio of hardwood to softwood chips in the composition recipe of industrially manufactured normal density 28 mm particleboards significantly influences the formaldehyde emission and the physical properties of the boards. The lowest formaldehyde emission among the three studied recipes with different percentage of participation of the raw material was recorded for the 35/65 (%hardwood/%softwood) recipe, while all the other properties had better values in the case of the 25/75 (%hardwood/ %softwood) recipe.
2. The simple density reduction of particleboards is not a viable alternative because all properties are weakened; an additive is compulsorily required.
3. The addition of P-MDI isocyanate additive in the composition recipe of 28 mm thick particleboards with reduced density led to a significant improvement of formaldehyde emission, thickness swelling, surface absorption and bending strength. No significant differences were observed upon the modulus of elasticity, internal bond, and surface soundness.
4. The recipe of low density particleboards with 0.25% P-MDI allows a reduction by 46.37% of the formaldehyde emission compared to low density particleboards without additive and by 21.98% compared to normal density particleboards.
5. The maximum simultaneous reduction of density and formaldehyde emission is possible with 0.4% P-MDI isocyanate additive.

REFERENCES CITED

Akrami, A., Barbu, M.C., and Frühwald, A. (2014). "Characterization of properties of oriented strand boards from beech and poplar," *European Journal of Wood and Wood Products* 72(3), 393-398, DOI: 0.1007/s00107-014-0793-9

Akyldiz, M. H., Kesik, H.I., Oncel, M., and Olgun, C. (2015). "Evaluation possibilities of rice straw in particleboard industry," *PRO LIGNO* 11(4), 130-137.

Barbu, M.C. (2015). "Evolution of lightweight wood composites," in: *Proceedings of ICWSE 2015*, Brasov, Romania, ISSN: 1843-2689, pp. 21-26 (Keynote Address).

Bektaş, İ., Güler, C., Kalaycıoğlu, H., Mengeloğlu, F., and Nacar, M. (2005). "The manufacture of particleboards using sunflower stalks (*Heliantus annuus* L.) and poplar wood (*Populus alba* L.)," *Journal of Composite Materials* 39(5), 467-473, DOI: 10.1177/0021998305047098.

Dunky, M. (1998). "Urea-formaldehyde (UF) adhesive resins for wood," *International Journal of Adhesion and Adhesives* 18(2), 95-107. DOI: 10.1016/SO143-7496(97)00054-7

EN 310 (1993). "Wood-based panels: Determination of modulus of elasticity in bending and of bending strength," European Committee for Standardization, Brussels, Belgium.

EN 311 (2002). "Particleboards. Surface soundness of particleboards, test method," European Committee for Standardization, Brussels, Belgium.

EN 317 (1993). "Particleboards and fibreboards. Determination of swelling in thickness after water immersion," European Committee for Standardization, Brussels, Belgium.

EN 319 (1993). "Particleboards and fibreboards. Determination of tensile strength perpendicular to the plane of the board," European Committee for Standardization, Brussels, Belgium.

EN 320 (2011). "Particleboards and fibreboards. Determination of resistance to axial withdrawal of screws," European Committee for Standardization, Brussels, Belgium.

EN 323 (1993). "Wood-based panels: Determination of density," European Committee for Standardization, Brussels, Belgium.

EN 326-1 (1994). "Wood-based panels: Sampling and cutting of test pieces and inspection," European Committee for Standardization, Brussels, Belgium.

EN 382-1 (1993). "Fibreboards. Determination of surface absorption. Test method for dry process fibreboards," European Committee for Standardization, Brussels, Belgium.

EN 717-3 (1996). "Wood-based panels: Determination of formaldehyde release. Formaldehyde release by the flask method," European Committee for Standardization, Brussels, Belgium.

Güler, C., Özen, R., and Kalaycıoğlu, H. (2001). "Some of the technological properties of cotton (*Gossypium hirsitum* L.) stalks particleboards," *KSU Journal Science and Engineering* 4(1), 99-108.

Kalaycıoğlu, H., and Nemli, G. (2006). "Production composite particleboard from kenaf (*Hibiscus cannabinus* L.) stalks," *Industrial Crops and Products* 24, 177-180. DOI: 10.1016/j.indcrop.2006.03.011

Lüdtke, J., Welling, J., Thömen, H., and Barbu, M. C. (2007). "Verfahren zum Herstellen einer Sandwichplatte bzw. Leichtbau-Holzwerkstoffplatte," European Patent DE 10 2007 012 597.8AZ/13.03.07.

Malanit, P., Barbu, M.C., and Frühwald, A. (2010). "Physical and mechanical properties of oriented strand lumber made from an Asian bamboo (*Dendrocalamus asper*

Backer)," *European Journal of Wood and Wood Products* 69(1), 27-36. DOI: 0.1007/s00107-009-0394-1

Monteiro, S., Martins, J., Magalhaes, F.D., and Carvalho, L. (2016). "Low-density wood-based particleboards bonded with foamable sour cassava starch: Preliminary studies," *Polymers* 8(354), 1-11, DOI: 10.3390/polym8100354

Pallant, J. (2007). *SPSS. Survival Manual. A Stept-by-Step Guide to Data Analysis using SPSS Version 15. Third Edition*. McGraw Hill, Open University Press.

Poppensieker, J., and Thömen, H. (2005). "Wabenplatten für den Möbelbau," Zentrum Holzwirtschaft, Universität Hamburg.

Article submitted: September 21, 2017; Peer review completed: November 12, 2017; Revised version received: December 17, 2017; Accepted: December 18, 2017; Published: January 5, 2018.
DOI: 10.15376/biores.13.1.1289-1302