WOOD RESEARCH
58 (2): 2013
265-274

PARTICLEBOARDS ENGINEERED THROUGH SEPARATE LAYER BONDING

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(Received March 2011)

ABSTRACT

16-mm thick three-layer particleboards of densities 600 and 660 kg.m^{-3} were manufactured in a 2-step procedure: (I) manufacturing of face and core layers as separate one-layer "component boards" and (II) bonding (assembling) of "component boards" into three-layer board. Industrial pine as well as fibrous willow and robinia chips were used as raw materials. UF, PVAc and EPI resins were used as binders. MOR, MOE and IB were determined for the manufactured boards. A 2-step procedure allows to obtain advantageous cross-sectional density profile revealing high-density layers (900 kg.m^{-3}). Regardless of the binder, the highest mechanical parameters were obtained for the willow boards. The resultant performance of the three-layer boards is strongly affected by the parameters of assembling the "component boards".

KEYWORDS: Particleboards, willow, robinia, density profile.

INTRODUCTION

Intense development of wood based panels results in increased demand for raw materials. For the Polish manufacturers (exception for the plywood), the main resources are green wood: pulpwood and small pole wood as well as the waste wood generated by all wood industry sectors during machining. However, these supplies are not sufficient. Since 2004, the wood based composites industry deals with wood deficit at the level ca. 20 %, while waste wood from the whole wood industry is utilized almost entirely (Hikiert and Oniśko 2006, Mirski and Dziurka 2011). Thus, it seems obvious that search for new resources is reasonable and justified.

In literature there are many reports on utilizing of fast-growing species like willow and poplar (Kowaluk et al. 2010, Kuzovkina and Volk 2009) as well as on a wide range of lignocellulosic materials like straw (Delmotte et al. 2003, Grigoriou 2000), kenaf (Kalaycioglu and Nemli 2006), bagassa (Nada and Hassan 1999), sunflower (Khristovi et al. 1996), cotton (Guler and Ozen 2004), corn (Donghai and Xiuzhi 2002), tea leaves (Jin-shu et al. 2006), coconut fiber (Khedari et al. 2003).

It must be stressed that using alternative raw materials usually results in deterioration of mechanical properties when compared to the standard boards (Gamage 2009, Nemli 2007, Niemz 1993). The mechanical properties of the wood particle composites strongly depends on the size and geometry of the particles (Kociszewski et al. 2012).

In general, it is commonly agreed that the higher density of face layers, the higher modulus of rupture of a board. As Keylwerth (1958) reported the face layers of particleboards bear 2/3 of bending moment. The cross-sectional density profile - flat or U-shaped – is strongly correlated with modulus of rupture, modulus of elasticity or internal bond observed for the particleboards (Wong et al. 1999, 2003).

Although an idea of manufacturing particleboards through separate layer bonding, comes from layered composites technology, which could be more expensive than conventional one-step technology, however it could result in improved mechanical performance of the boards, so that it has been investigated and described in this paper.

MATERIAL METHODS

16-mm thick three-layer particleboards of densities 600 and 660 kg.m^{-3} were manufactured in a 2-step procedure: (I) manufacturing of face and core layers as separate one-layer "component boards" and (II) bonding (assembling) of "component boards" into three-layer board.

Material

The raw materials used for particleboards production were as follow:

- Willow (*Salix viminalis* L.) fibrous chips prepared in a laboratory chipper (2.5 % moisture content for face layer and 3.4 % moisture content for core layer), basic density – 520 kg.m^{-3}
- Robinia (*Robinia pseudoacacia* L.) fibrous chips prepared in a laboratory chipper (2.2 % moisture content for face layer and 2.8 % moisture content for core layer), basic density – 713 kg.m^{-3}
- Industrial pine (*Pinus sylvestris* L.) chips (2.8 % moisture content for face layer and 2.6 % moisture content for core layer), basic density – 520 kg.m^{-3}.

In Fig. 1 fraction shares of used chips were compared.

Commercial resins used as binders:

- UF resin – used at step I and step II
- EPI adhesive system – used at step II
- PVAc – used at step II

Characteristics of applied adhesives were shown in Tab. 1.

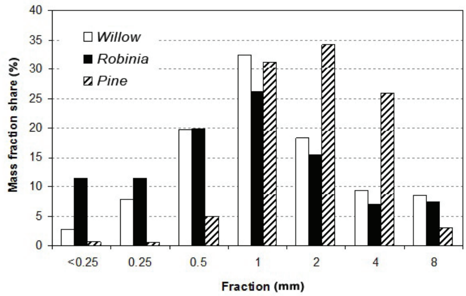

Fig. 1: Fraction shares of used chips.

Tab. 1: Characteristics of applied adhesives.

Adhesive	EPI	PVAc	UF
Classification for water resistance	D4	D3	D1
Dry matter	99 %	50 %	67 %
Brookfield viscosity	9000 mPas	11000 mPas	600 mPas
Curing time* at 20°C/100°C	1320s/120s	420s/120s	840s/110s
pH	7	3	8

* in case of PVAc the time to handling strength was given

Particleboards preparation

Step I

One-layer "component boards" were prepared in three variants for each raw material i.e. willow, robinia and industrial pine chips (Tab. 2).

Tab. 2: Component boards prepared at step I.

Face layer	Core layer	Core layer
density 900 $kg.m^{-3}$ *	density 462 $kg.m^{-3}$ *	density 550 $kg.m^{-3}$ *
thickness 2.5 mm	thickness 11 mm	
glue load 12 %	glue load 10 %	

* the component densities were set at the levels providing resultant overall density of a board respectively 600 and 660 $kg.m^{-3}$ (face layers density x face layers thickness share + core layer density x core layer thickness share)

Formulation of the glue:
UF resin – 50 parts by weight
hardener (10 % $(NH_4)_2SO_4$) – 1.5 parts by weight
water – 15.5 parts by weight

The glue was spread pneumatically onto the chips and then a mat was formed and hot-pressed.

Pressing parameters:
- maximum unit pressure 2.5 MPa
- temperature 180°C
- time 180 s (face layer), 240 s (core layer) – pressing times were set empirically during the initial experiments. They were longer than typical industrial times to avoid the delamination of the panel (which is thin) caused by the steam escaping out of the mat.

During this time the press pressure was gradually reduced.

Step II

Assembling of the "component boards" into three-layer board was performed at 20 or 110°C under the conditions presented in Tab. 3. Pressing parameters were determined on the total overheating and glue curing time basis (Kurowska et al. 2010), as well as according to the reactivity of the bonding agents shown in Tab. 1.

Tab. 3: Bonding parameters at step II.

Glue	UF	EPI	PVAc
20°C			
Formulation (parts by weight)	resin – 100 85 % formic acid – 1.6 water – 10 wheat flour – 20	resin – 100 hardener – 25	resin – 100
Pressing time	20 min	30 min	10 min
Glue load	160 g.m^{-2}		
Unit pressure	1.0 MPa		
110°C			
Formulation (parts by weight)	resin – 100 10 % $(NH_4)_2SO_4$) – 5 water – 10 wheat flour – 20	resin – 100 hardener – 25	resin – 100
Pressing time	4 min	3 min	3 min
Glue load	160 g.m^{-2}		
Unit pressure	1.0 MPa		

Mechanical tests of the studied boards

The manufactured boards were conditioned in a laboratory room for 48 hours, then cut into test specimens complying with the respective EN standards: 310: 1994 – 10 specimens in each series, EN 319: 1999 – 10 specimens in each series, density profile – 3 specimens in each series, and subjected to the following tests:

The significance of differences between means was determined by the Student t-test at 0.05 significance level.

RESULTS AND DISCUSSION

The cross-sections of the tested boards were shown in Fig. 2. Respective density profiles were shown in Figs. 3 and 4. Mechanical properties are tabulated in Tabs. 4-6.

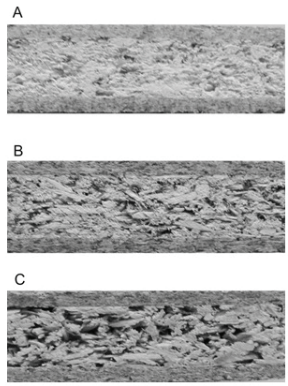

Fig. 2: Engineered particleboards : A – robinia, B – willow, C – pine.

Tab. 4: Mechanical properties of the studied particleboards made of pine chips.

VARIANT		Density	MOR	sd MOR	MOE	sd MOE	IB	sd IB
		(kg.m^{-3})	(N.mm^{-2})					
Nominal density 600 kg.m^{-3}	UF 20°C	610	14.3	1.5	1962	245	0.27	0.02
	UF 110°C	620	16.6	1.7	2462	199	0.30	0.04
	PVAc 20°C	623	15.0	1.7	2068	281	0.28	0.04
	PVAc 110°C	623	17.1	1.8	2670	95	0.32	0.03
	EPI 20°C	620	16.2	1.3	2212	255	0.27	0.03
	EPI 110°C	627	19.0	2.7	2909	163	0.32	0.04
Nominal density 660 kg.m^{-3}	UF 20°C	684	13.9	1.6	2240	152	0.39	0.03
	UF 110°C	692	18.9	1.5	2793	125	0.38	0.05
	PVAc 20°C	689	14.8	1.6	2759	306	0.41	0.03
	PVAc 110°C	683	17.7	1.9	2475	110	0.40	0.05
	EPI 20°C	671	17.5	2.7	2363	365	0.43	0.02
	EPI 110°C	678	19.8	2.4	2637	119	0.43	0.04

Tab. 5: Mechanical properties of the studied particleboards made of willow chips.

VARIANT		Density ($kg.m^{-3}$)	MOR	sd MOR	MOE	sd MOE	IB	sd IB
			($N.mm^{-2}$)					
Nominal density 600 $kg.m^{-3}$	UF 20°C	629	19.8	1.8	2389	98	0.36	0.03
	UF 110°C	622	20.1	2.5	2446	167	0.43	0.05
	PVAc 20°C	629	20.1	2.5	2748	144	0.34	0.02
	PVAc 110°C	627	21.0	3.3	2482	132	0.39	0.05
	EPI 20°C	620	22.7	2.5	2471	117	0.35	0.04
	EPI 110°C	617	19.8	2.4	2459	287	0.35	0.04
Nominal density 660 $kg.m^{-3}$	UF 20°C	676	18.2	2.0	2506	250	0.47	0.02
	UF 110°C	689	19.0	2.2	2513	98	0.48	0.02
	PVAc 20°C	684	23.5	2.6	2582	177	0.46	0.05
	PVAc 110°C	688	24.3	1.7	2885	83	0.45	0.06
	EPI 20°C	692	22.4	2.7	2533	333	0.50	0.06
	EPI 110°C	686	22.4	2.4	2909	197	0.53	0.04

Tab. 6: Mechanical properties of the studied particleboards made of robinia chips.

VARIANT		Density ($kg.m^{-3}$)	MOR	sd MOR	MOE	sd MOE	IB	sd IB
			($N.mm^{-2}$)					
Nominal density 600 $kg.m^{-3}$	UF 20°C	617	20.6	1.9	2240	143	0.33	0.02
	UF 110°C	620	21.5	2.4	2386	190	0.29	0.03
	PVAc 20°C	616	24.4	2.6	2623	340	0.32	0.03
	PVAc 110°C	629	24.3	2.6	2603	283	0.31	0.04
	EPI 20°C	621	23.8	2.9	2584	107	0.34	0.05
	EPI 110°C	620	23.3	2.3	2653	249	0.30	0.04
Nominal density 660 $kg.m^{-3}$	UF 20°C	680	22.1	2.8	2475	104	0.39	0.05
	UF 110°C	682	21.7	2.1	2457	70	0.37	0.05
	PVAc 20°C	677	23.1	3.2	2709	194	0.42	0.05
	PVAc 110°C	693	23.1	1.4	2586	116	0.47	0.04
	EPI 20°C	686	25.4	3.5	2920	114	0.43	0.03
	EPI 110°C	688	24.5	2.7	2907	277	0.37	0.03

The resultant densities of the manufactured boards – independently on the material, type of binder or pressing temperature – slightly exceeded nominal values (Figs. 3 and 4). For the nominal density of 600 $kg.m^{-3}$, the final densities ranged from 610 to 629 $kg.m^{-3}$, while for the nominal 660 $kg.m^{-3}$, densities between 671 and 693 $kg.m^{-3}$ were obtained, however, the maximum deviation from the nominal density did not exceed 5 %.

The deviations are caused by additional glue line between the layers, which affected the final weight of the boards and subsequent increase in density. Cross-sectional density profiles are not U-shaped, but three-layer structure can be observed instead. Such a structure may possibly increase MOR and MOE of the boards.

As Fig. 3 indicates for the boards of density 600 kg.m^{-3}, decrease in the core layer is greater than that for the boards of density 660 kg.m^{-3} (Fig. 4). The density profiles are affected by the presence of the glue lines which can be revealed as peaks denoting local increase in density.

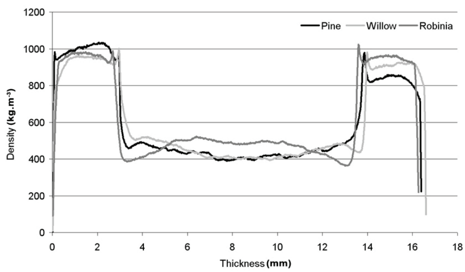

Fig. 3: Typical density profile of a particleboards of nominal density 600 kg.m^{-3} assembled using UF resin at 110 °C.

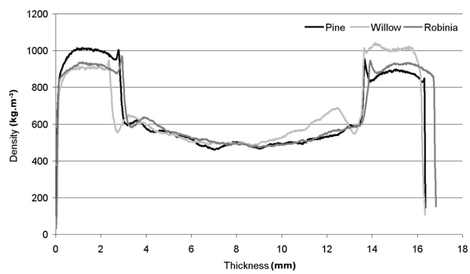

Fig. 4: Typical density profile of a particleboards of nominal density 660 kg.m^{-3} assembled using UF resin at 110 °C.

The obtained MOR values in all cases were higher than that required by the EN 312: 2010 for the P2 type boards i.e. 11 N.mm^{-2}. In general it can be stated that the highest strengths were observed for the robinia boards (20.6 – 24.4 N.mm^{-2} for nominal density 600 kg.m^{-3} and 21.7 – 25.4 N.mm^{-2} for 660 kg.m^{-3}). The lowest values were obtained for the pine boards (14.3 – 19.0 N.mm^{-2} for nominal density 600 kg.m^{-3} and 13.9 – 19.8 N.mm^{-2} for 660 kg.m^{-3}). Regardless of the adhesive type, assembling temperature or density, the differences are statistically significant. The phenomenon can be explained by the greater dimensions of the chips in the core layer (Fig. 5) which resulted in high roughness of the surface. Due to the roughness and subsequent substantial thickness of the glue line, the adhesive joint was weakened and ease of delamination occurred. MOR values should not be lowered by the break of the adhesive bonds caused by the second pressing step temperature, because, according to Hirata et al. (1991), thermal degradation of the cured UF resin starts at 220°C.

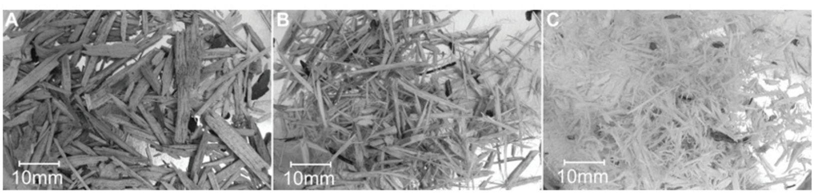

Fig. 5: The chips used for the core layer: A – industrial pine, B – willow, C – robinia.

Fig. 6 presents a pine board specimen delaminated during bending test. It is worth mentioning that delaminations were not observed for willow or robinia boards. Since the overall strength of a board is mainly determined by the strength of the face layers – which bear maximum tensile and compression stress – comparable MOR and MOE values for both 600 and 660 kg.m^{-3} series came from the face layers of nominal density 900 kg.m^{-3}.

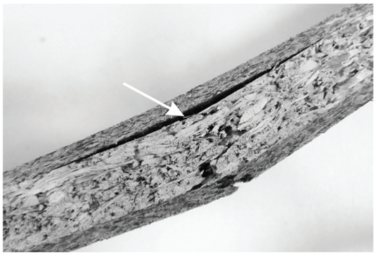

Fig. 6: Pine board specimen delaminated during bending test assembled using UF at 20°C.

Fig. 7: Specimen fractured within the core layer during IB test.

MOE met the requirements of the EN 312: 2010 standard for P2 type boards for all the series observed i.e. 1600 N.mm^{-2}. Thus, independently on the binder used both willow and robinia boards exhibited MOE values ranging from 2240 to 2748 N.mm^{-2} for the nominal density 600 kg.m^{-3} and 2457 – 2920 N.mm^{-2} for 660 kg.m^{-3}. The boards made of industrial pine chips exhibited higher variation of MOE value: 1962 – 2909 N.mm^{-2} for 600 kg.m^{-3} and 2240 – 2793 N.mm^{-2} for 660 kg.m^{-3}. The deterioration of the properties results – as for MOR discussed above – from the greater size of the chips.

The component boards of density 900 kg.m^{-3} used as face layers provided repeatable MOR values for all the series, so that correlation of MOR with the type of material (willow, robinia) or type of adhesive (UF, EPI, PVAc) is not clear. At 20°C only the ease of delamination for UF-assembled boards can be noticed.

The obtained IB values ranged from 0.27 to 0.43 N.mm^{-2} for nominal density 600 kg.m^{-3} and 0.37 – 0.53 N.mm^{-2} for 660 kg.m^{-3} which proved that the boards of the latter series complied with the requirements of the EN 312: 2010 i.e. 0.35 N.mm^{-2} (P2 type board), while amidst the 600 kg.m^{-3} series only willow boards met the respective requirements (0.34 – 0.43 N.mm^{-2}). The other series met only requirement for P1 type board (0.24 N.mm^{-2}). The highest IB values were observed for the willow boards, however, IBs for robinia and pine series remained comparable independently on the material used. Statistically significant increase in IB value for the willow boards - when compared to that of pine and robinia - comes from their density (520 kg.m^{-3}) and dimensions of the chips and subsequent better compaction of the mat which is consistent with previous reports by Suchsland and Woodson (1991). Moreover, the IB was not affected by the type of adhesive. But it was noticed that the boards assembled at 20°C using UF exhibited substantial rate of adhesive failure of the glue line. Such specimens were excluded from further data processing. Only the data obtained for properly fractured specimens – within the core layer (Fig. 7) – was used in calculations.

It should be stressed that the presented values determined the IB of the weakest layer – i.e. core layer of nominal density 462 and 550 kg.m^{-3}.

When boards of nominal core layer density 550 and 426 kg.m^{-3} are compared (Tab. 4-6), it is clear that the IB obtained for the latter series are lower by 23 % (robinia, willow) and by 28 % (pine).

CONCLUSIONS

The cross-sectional density profiles of the engineered particleboards manufactured through the 2-step procedure reveal outer high density zone (900 kg.m^{-3}) providing satisfactory mechanical properties (MOR and MOE) even for the boards of low average density (e.g. 600 kg.m^{-3}). It was shown that the resultant performance of the boards was influenced by the type of adhesive and assembling parameters. However, the results allowed to conclude that the willow and robinia boards exhibited higher strengths than those for the boards made of industrial pine chips. The IB values of the manufactured boards were solely associated with the type of the raw material and the density of the core layer. The type of binder used for assembling did not influence the IB. Thus the highest IB was obtained for the willow boards.

ACKNOWLEDGMENT

This study has been carried out with the financial support of the Ministry of Science and Higher Education in Poland, in years 2007 – 2010, project number N 309 1068 33.

REFERENCES

1. Donghai, W., Xiuzhi, S., 2002: Low density particleboard from wheat straw and corn pith. Ind. Crops Prod. 15(1): 43–50.
2. EN 310, 1994: Wood-based panels - Determination of modulus of elasticity in bending and bending strength.
3. EN 312, 2010: Particleboards – Specifications.
4. EN 319, 1999: Particleboards and fibreboards; determination of tensile strength perpendicular to the plane of the board.
5. Gamage, N., Setunge, S., Jollands, M., Hague, J., 2009: Properties of hardwood saw mill residue-based particleboards as affected by processing parameters. Ind. Crops Prod. 29(1): 248–254.
6. Grigoriou, A.H., 2000: Straw-wood composites bonded with various adhesive system. Wood Sci. Technol. 34(4): 355–365.
7. Guler, C., Ozen, R., 2004: Some properties of particleboards made from cotton stalks (*Gossypium hirsitum* L.). Holz als Roh- und Werkstoff 62(1): 40–43.
8. Hikiert, M.A., Ońiśko, W., 2006: Strategy of the polish wood-based panels industry development to 2013. Publisher: Wood Technology Institute, Poznan, Poland (in Polish).
9. Hirata, T., Kawamoto, S., Okuro, A., 1991: Pyrolysis of melamine – formaldehyde and urea – formaldehyde resins. J. Appl. Polym. Sci. 42(12): 3147-3163.
10. Jin-shu, S., Jian-zhang, L., Yong-ming, F., Hong-xia, M., 2006: Preparation and properties of waste tea leaves particleboard. For. Stud. China 8: 41–45.
11. Kalaycioglu, H., Nemli, G., 2006: Producing composite particleboard from kenaf (*Hibiscus cannabinus* L.) stalks. Industrial Crops and Products 24(2): 177-180.
12. Keylwerth, R., 1958: Zur Mechanik der mehrschichtigen Spanplatten. Holz als Roh- und Werkstoff 16(11): 419–430.
13. Khedari, J., Charoenvai, S., Hirunlabh, J., 2003: New insulating particleboards from durian peel and coconut coir. Build. Environ. 38(3): 435–441.

14. Khristova, P., Yossifov, N., Gabir, S., 1996: Particle board from sunflower stalk: Preliminary Trials. Bioresource Technology 58(3): 319–321.
15. Kociszewski, M., Gozdecki, C., Wilczyński, A., Zajchowski, S., Mirowski, J., 2012: Effect of industrial wood particle size on mechanical properties of wood-polyvinyl chloride composites. Eur. J. Wood Prod. 70(1/3): 113-118. DOI 10.1007/s00107-011-0531-5.
16. Kowaluk, G., Pałubicki, B., Frąckowiak, I., Marchal, R., Beer, P., 2010: Influence of ligno-cellulosic particles on tribological properties of boards. Eur. J. Wood Prod. 68(1): 95–98.
17. Kurowska, A., Borysiuk, P., Mamiński, M., Zbieć, M., 2010: Veneer densification as a tool for shortening of plywood pressing time. Drvna Industrija 61(3): 193–196.
18. Kuzovkina, Y.A., Volk, T.A., 2009: The characterization of willow (*Salix* L.) varieties for use in ecological engineering applications: Co-ordination of structure, function and autecology. Ecol. Eng. 35(8): 1178–1189.
19. Mirski, R., Dziurka, D., 2011: The utilization of chips from comminuted wood waste as a substitute for flakes in the oriented strand board core. Forest Products Journal 61(6): 473-477.
20. Nada, A., Hassan, M.L., 1999: Recycled newsprint as a fibre source for low-density bagasse particleboard manufacture. J. Sci. Ind. Res. 58(8): 616–619.
21. Nemli, G., Aydın, I., Zekoviç, E., 2007: Evaluation of some of the properties of particleboard as function of manufacturing parameters. Mater. Design 28(4): 1169–1176.
22. Niemz, P., 1993: Physik des Holzes und der Holzwerkstoffe. DRW-Verlag, Stuttgart, 243 pp.
23. Suchsland, O., Woodson, G.E., 1991: Fibreboards manufacturing practices in United States. USDA Forest Service, Agricultural Handbook No. 640, Washington D.C., 263 pp.
24. Wong, E., Yang, M., Zhang, M., Wang, Q., Nakao, K., Kawai, S., 2003: Analysis of the effects of density profile on the bending properties of particleboard using finite element method (FEM). Holz als Roh- und Werkstoff 61(1): 66–72.
25. Wong, E., Zhang, M., Wang, Q., Kawai, S., 1999: Formation of the density profile and its effects on the properties of particleboard. Wood Sci. Technol. 33(4): 327–340.
26. Zhang, Y., Lu, X., Pizzi, A., Delmotte, L., 2003: Wheat straw particleboard bonding improvements by enzyme pretreatment. Holz als Roh- und Werkstoff 61(1): 49–54.

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