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Properties of particleboard produced from post-industrial UF- and PF-bonded plywood

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Abstract
An approach based on the recycling of waste plywood as a recovered wood resource for the particleboard industry is described. It is demonstrated that post-industrial urea- (UF) and phenol-formaldehyde (PF) bonded plywood can be effectively shredded to the form of the recovered particles that can be a valuable material in particleboard manufacturing. The effects of shredding conditions and binder type on the recovered particles characteristics and the mechanical properties of the particleboards were analyzed. It is shown that the substitution of 20–100% of virgin particles with the recovered material is possible without affecting the performance of the particleboard.

1 Introduction

Although the volume of wood grown every year is substantial, the harvest is lower than the demand. In addition, the high competition with the energetic sector for wood generates an increase in pricing. Subsequently, wood industry—including particleboard sector—experiences a deficiency of raw material (Mantau 2010). The European survey "EUwood" showed that wood deficiency would reach 200 and 300 million m^3 in 2025 and 2030, respectively (Zbořil and Pesci 2011).

Wastes from forestry, post-industrial waste wood (e.g. sawdust, sawmill particles, wastes from panel edging, particles) and post-consumer waste wood (e.g. used furniture, demolition wood, window frames and wood-based panels, palettes, boxes, solid wood packaging) have become a widely recognized feedstock for wood-based composite industry (Hillring et al. 2007; Merl et al. 2007; van Benthem et al. 2007; Vefago and Avellaneda 2013; Diyamandoglu and Fortuna 2015; Kurowska 2015, 2016). Some countries in Europe use waste wood, especially post-industrial wastes, for the production of particleboards. The rate of waste wood in particleboard can reach 40%. The feedstock includes waste plywood, but the resource makes less than 5%. In Canada and U.S. particleboards manufactured according to LEED (Leadership in Energy and Environmental Design) system contain minimum 10% of waste wood and are bonded with formaldehyde-free binders (e.g. PMDI) (http://www.usgbc.org). In the present work, it was demonstrated that the content of post-industrial waste wood can be increased above that limit.

Plywood and laminated veneer lumber (LVL) contain the highest amounts of the binders—typically 12–15% wt based on solids. Amino resins and phenolic resins are not classified as hazardous. Only formaldehyde which can be released from the urea-formaldehyde (UF) resins has been classified in category 1B as carcinogenic to humans (Commission Regulation (EU) 2014).

The problem of the use of recycled particles in particleboard manufacturing is hardly discussed in the literature. Numerous approaches have been discussed in the literature. Lykidis and Grigoriou (2008) utilized four different particle-recovery hydrothermal treatments in order to recycle particles from particleboards and use them in the production of new ones. Höglmeier et al. (2014) proposed utilizing waste wood in a cascading system. Kim and Song (2014) report the environmental aspects like reduced amount of carbon dioxide and energy savings when recovered wood is looped to production. The review papers mainly consider a reuse of the waste plywood without its transformation (Vefago and Avellaneda 2013; Diyamandoglu and Fortuna 2015). Czarnecki et al. (2003) investigated substitution of industrial particles in particleboard manufacturing for the particles recycled from

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UF- and PF-bonded raw and laminated particleboards as well as for the particles from UF-bonded MDF. Demirkir and Çolakoğlu (2007) examined formaldehyde emission from particleboards manufactured with waste veneers, plywood edgings or veneer peeler cores.

Unfortunately, the shredding procedure was not reported. The conditions of shredding process determine a range of particle properties (Palmqvist et al. 2005; Hernández et al. 2014). Thus, a complex analysis of the particles is justified since their properties determine the performance of the final product—i.e. panels (Nemli et al. 2007; Nazerian et al. 2011). Fractional composition and bulk density are the key factors affecting not only particles blending, mat forming and pressing (Suchsland and Woodson 1991; Gamage et al. 2009; Nazerian et al. 2011), but also determine the size of the transportation and production equipment as well as the necessary storage space.

The dimensions of particles strongly affect the properties of particleboards. In general it is agreed that short and thick particles reduce moduli of rupture and elasticity (Mundy and Bonfield 1998). On the other hand, such particles provide a more uniform panel structure, so that internal bond is increased. More compact structure of the core layer renders lowered thickness swelling and absorption (Rackwitz 1963; Hutschneker 1975; Sackey et al. 2008; Nazerian et al. 2011). It was demonstrated that when glue load was constant, but the content of fine fractions and dust increased, fine particles tend to absorb a disproportionate quantity of the adhesive which reduces the quantity of adhesive available for bonding between the particles. Subsequently, physical and mechanical properties of particleboards are lowered (Nemli et al. 2007; Sackey et al. 2008).

The objective of this work was to demonstrate and examine the properties of particleboard produced from post-industrial UF- and PF-bonded plywood. In industrial conditions particles are produced usually from two-step shredding: (1) round wood is cut in chippers, then (2) chips are shredded to particles in flakers. While the wastes like edgings, trimmings, solid wood packaging items are shredded in the shredders. Such approach makes particleboard production more efficient. Another objective of the studies was to assess whether it was possible to use a wood shredder for producing particles from waste plywood that exhibit properties as close as possible to those of the industrial core layer particles.

2 Materials and methods

2.1 Waste plywood

Urea-formaldehyde (UF)- and PF-bonded waste pine (*Pinus sylvestris* L.) plywood in the amount of 1 tonne was obtained from two plants in Poland. The material was generated in the edging operations. The plywood specification was as follows: thickness 7, 12, 16 and 22 mm; density 660 kg/m^3; moisture content 6%. The plywood was composed of the odd number of veneers 1.4, 1.8, 2.2 or 2.5 mm thick. The industrial binder formulations contained about 30% solid additives (i.e. ammonium sulfate and rye flour in UF; rye flour in PF). 1 m^3 of plywood contained 75 kg of binder that made *ca*. 14% of dry wood weight.

2.2 Shredding of waste plywood

A wood shredder with 10-, 14-, 25- and 38-mm mesh screens and a constant knife-counter knife gap 2.21 mm was used. To determine the effect of the binder on shredding and resultant properties of the recovered particles, UF and PF-bonded plywood was shredded separately. The core layer industrial pine particles (P_CL) were used as a reference. Six grades of the recovered particles after shredding of pine plywood were obtained: 10_UF, 10_PF, 14_UF, 14_PF, 25_PF, 38_PF (where: the number denotes screen mesh size, UF or PF denotes the binder type).

2.3 Particles recovered from waste plywood

The present study contains a comparison of the properties of particles recovered from waste plywood and industrial particles: fractional composition and bulk density were determined. Moisture content was determined gravimetrically with 0.1% accuracy.

A laboratory sorter with 10.00, 8.00, 6.00, 4.00, 2.00, 1.25, 0.63, 0.32 mm mesh sieves and dust container was used. Particles were sorted in 100-g batches. Twelve representative replicates were done for each batch. Sorting time was 20 min. Once sorted, the fractions were weighted with an accuracy of 0.01 g. Finally, each mixture was divided into four groups: large particles (4.00–10.00 mm), medium particles (2.00 and 1.25 mm), fine particles (0.63–0.32 mm) and dust. Bulk density was determined according to the procedure implemented in industry: particles were poured into a 0.002 m^3 steel container (100 mm diameter, 260 mm height), weighted and the outcome was recalculated to 1 m^3 volume.

Table 1 Compositions of the mixtures of particles

Mixture	Recovered particles content (%)	
	UF	PF
I	100	0
II	75	25
III	50	50
IV	25	75
V	0	100

Table 2 UF adhesive formulation

Component	Face layer (ppw)	Core layer (ppw)
UF	50.0	50.0
10% aq. $(NH_4)_2SO_4$	1.0	1.5
Water	15.0	14.5

2.4 Mixture of recovered wood particles

Five mixtures of the recovered particles were prepared. The content of the particles with UF- and PF-resin in the respective mixtures is shown in Table 1.

2.5 Preparation of particleboards

Three-layer particleboards (16-mm thick, 650 kg/m^3) were prepared. Nine particleboards of each type were prepared. The face/core layer rate was set at 25%/50%. Paraffin emulsion was spread over the particles at 1% rate. UF-resin load was 12 and 10%, respectively, for face and core layer. The adhesive formulation is presented in Table 2.

The parameters of the hot pressing mats were as follows: unit pressure 3 MPa, platen temperature 180 °C, time 300 s. Mat core temperature, pressure and thickness were monitored in real time with accuracy ± 0.01 °C, ± 0.01 MPa and ± 0.01 mm, respectively. Temperature in the mat core was monitored by a Fe–CuNi thermocouple. The face and core layer industrial particles were obtained from a particleboard plant in Poland. Their fractional compositions were typical of industrial applications. The content of the particles mixture (Table 1) in the core layers was 20, 40, 60, 80 or 100%. The boards made of industrial particles only were used as the reference. Then, twenty-six variants of the boards of various core layer compositions were produced.

2.6 Properties of particleboards

The manufactured boards were characterized in terms of: density (MD) (EN 323 1993), thickness swelling (TS) after 24-hr soaking (EN 317 1993), modulus of rupture (MOR) and modulus of elasticity (MOE) (EN 310 1993), internal bonding (IB) (EN 319 1993). Physical and mechanical properties of each type of particleboard were determined for 15 samples. Statistical analysis was performed using STATISTICA version-12 software of StatSoft, Inc. company. The statistical analysis of the differences between the experimental grades and the reference was carried out at a significance level of 0.050.

3 Results and discussion

Fractional composition of the reference particles (P_CL) was as follows: 25.7, 59.1, 13.8, 1.4% for large, medium, fine particles and dust, respectively.

The shredding yielded three types of particles: those similar to industrial P_CL particles, splinter particles, and “layered particles” (Fig. 1a). Splinter particles were irregular in cross-section and larger than P_CL particles. “Layered particles” were built of two or three bonded layers. The particles of that type were produced by tearing out the fragments of plywood without delamination of the neighboring veneers. Some portion of the particles had one or both surfaces covered with the cured adhesive (UF—Fig. 1b; PF—Fig. 1c, d) and wood fibers as well (Fig. 1b, d) which indicated bondline wood failure upon shredding. Thus, it is apparent that both wood and bondline strengths affected the morphology of the particles. In all the examined groups, the UF-covered particles were found, however the PF-covered particles dominated in the “layered particles” type. The phenomenon resulted from the fact that the dry strength of UF bondline was comparable to that of wood, while the PF strength was even higher. The share of the “layered particles” was low and did not significantly affect the differences between fractional compositions of UF- and PF-bonded particles mixtures.

It is worth noting that the layer of cured adhesive is a mechanical barrier for a liquid adhesive upon secondary glue spreading (Deppe and Ernst 1996; Lee et al. 2002; Pocius 2002).

Fractional compositions of the P_CL particles and the recovered particles are shown in Fig. 2. It was found that particle size distribution in each mixture was similar, except for the 25_PF and 38_PF fractions. Statistical analysis of the fractional compositions showed no significant difference between 10_UF and 10_PF nor between 14_UF and 14_PF mixtures. Thus, it seems apparent that the type of the binder did not affect the fractional composition of the recovered particles. That is why a wood shredder equipped

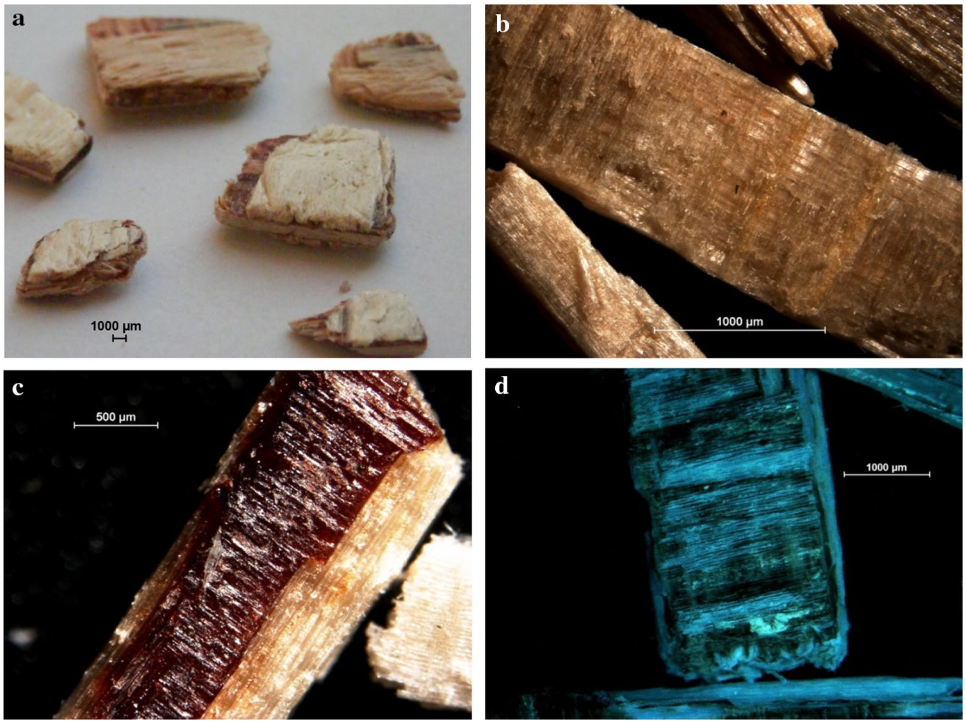


Fig. 1 Recovered particles from waste plywood: **a** "layered particles", **b** UF- and wood fibers covered, **c** PF-covered, **d** PF- and wood fibers covered

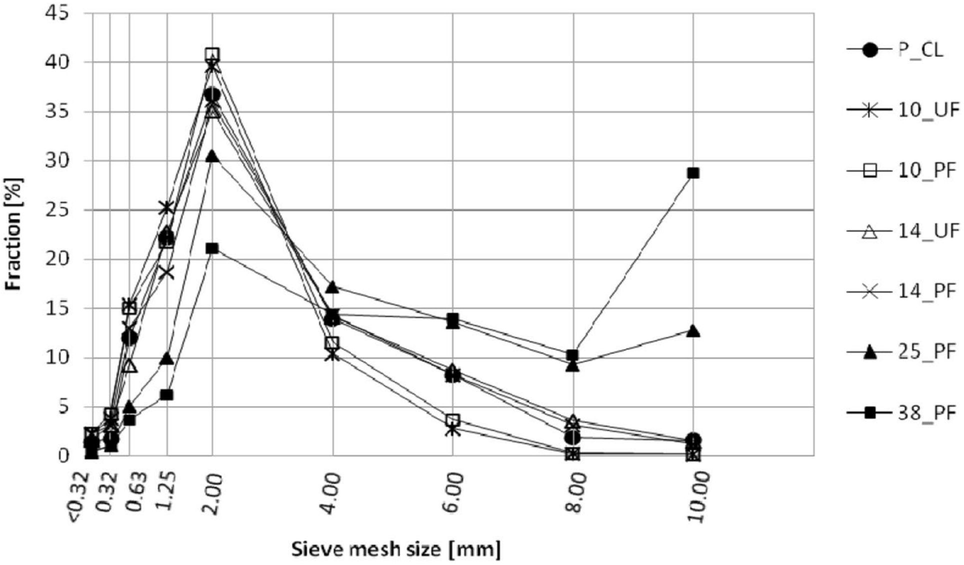


Fig. 2 Fractional composition of the industrial particles (P_CL) and particles recovered from waste plywood

with 25- and 38-mm mesh screens was used for shredding PF-bonded plywood only. The 2.00-mm fraction comprised the majority (30.5–41.2%) both of the industrial P_CL and in the recovered particles. In 38_PF mixture, the 10.00-mm fraction was dominating (28.8%).

The use of a 14-mm mesh screen in the shredder yielded a particle size distribution similar to that of the industrial P_CL particles. In the recovered mixture large, medium and fine particles made up 27.4, 56.4, 14.3 and 1.9% dust, respectively. On the other hand, the use of 10-mm mesh screen resulted in 14.6, 63.8, 19.3% of the large, medium and fine fractions, respectively, and 2.3% dust. Such size distribution indicates that the use of a denser screen produced a higher share of the finer fractions. From the literature it is commonly known that the particleboards containing high amounts of fine particles and dust exhibit lower physical and mechanical properties (Nemli et al. 2007; Sackey et al. 2008).

In the 25_PF and 38_PF mixtures there were 2- and 2.5-times more large particles, respectively, when compared to

Table 3 Moisture content (MC) and bulk density of the studied particles

Mixture	M.C. (%)		Bulk density (kg/m^3)	
	Mean	Std. dev	Mean	Std. dev
P_CL	6.7	0.1	193	2
10_UF	7.5	0.2	327[a]	9
10_PF	7.0	0.1	313[a]	7
14_UF	6.9	0.3	319[a]	4
14_PF	7.2	0.3	291[a]	4
25_PF	5.9	0.2	284[a]	2
38_PF	5.8	0.4	250[a]	3

[a] Indicates statistically significant values at the significance level 0.05

the reference industrial P_CL particles. For 25- or 38-mm mesh screens, the dust content was reduced to 0.4 and 0.5% (25_PF and 38_PF mixtures, respectively).

The disintegration of plywood takes place in the gap between the knife and the counter knife. Since the gap was fixed at 2.21 mm and kept constant, the factor affecting resultant particle dimensions was a screen mesh size. Thus, it is clear that shredding of the post-industrial plywood on bigger mesh screens yielded reduced content of dust and fine fractions, as well as an increased content of large particles.

Moisture content and bulk density of the recovered particles are presented in Table 3. Bulk density of the industrial particles was 193 kg/m^3 for 6.7% moisture content. Bulk density of the recovered particles was significantly higher when compared to that of the industrial reference particles P_CL. The values determined for the mixtures produced with 10- and 14-mm mesh screens were higher by 66 and 58%, respectively. An increased bulk density of the recovered particles can be explained by veneer densification during plywood manufacturing as well as by the content of the cured binders in the material (Wang et al. 2006). Bulk density also depends on the shape and dimensions of the particles, so that fine particles and dust are more tightly packed in a volume unit. It is also postulated that the characteristics of the produced particles were affected by low moisture content in the waste plywood (5.8–7.5%) which eased an extra shredding through friction between particles into the shred-chamber. That is why the substantial amounts of dust and fine fractions were yielded.

Higher bulk density of the recovered particles can be an advantage for mat pressing process, since lower number of particles will be present in a mat volume unit and the total volume of empty space in a mat will be higher. Thus, heat transfer into the core of the mat will be easier and faster which may result both in the altered rheological properties of wood particles and the board density profile (Bolton et al. 1989; Humphrey and Bolton 1989; Hata et al. 1990; Thoemen and Humphrey 2001).

The results indicate that the 14_UF and 14_PF particles exhibited properties closest to those of the industrial P_CL series. Thus, these two grades were used for board manufacturing. It was found that the particle mixture used in the core layer (I–V) had no effect on the mat pressure curves, mat core temperature curve or mat thickness curve. Thus, the type of binder (UF, PF) was not a factor that affected the mat pressing. The representative real-time variations in the parameters are shown in Fig. 3.

The content of the recovered particles in the mixture affected neither the pressure curve nor mat thickness when compared to those of the reference, so that the target board thickness (16 mm) was achieved in 20–25 s.

It is worth noting that the amount of the recovered particles increased the dynamics of heat transfer. As a result a target mat core temperature was achieved in a shorter time. Taking into account the phenomenology reported by Graser (1962) and Bolton et al. (1989), the maximum effect was observed in phase II (water evaporation) that lasted from 20 to 120 s. In consequence, the time necessary to heat a mat bearing 20% of the recovered particles to 60, 80 and 100 °C was shortened by 22, 16 and 8%, respectively. Under alike conditions, times of heating a mat containing 100% recovered particles were 29, 25 and 15% shorter than those for the reference.

It is agreed that pressing time (t_p) can be adjusted by controlling gel time of the adhesive (t_g) and mat heating time

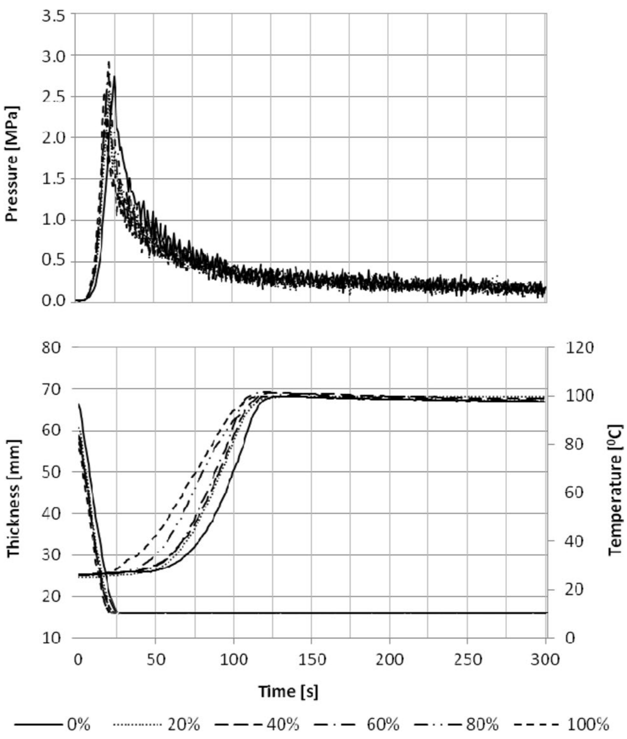


Fig. 3 Pressure, mat core temperature and mat thickness curves recorded in real-time upon pressing

(t_o). Thus, it is apparent from the relation $t_p = t_g + t_o$ that the shorter t_o is, the shorter overall t_p can be.

The presented results demonstrate that the mats bearing recovered particles require shorter pressing time than the industrial particle mats. For instance, 3 and 6% shorter pressing time were yielded for the mats with 20 or 100% of the recovered material, respectively.

The phenomena can be explained by the 58% higher bulk density of the recovered particles when compared to the industrial ones (P_CL). An increased share of the recovered particles resulted in a less compact structure of the core layer, so that, steam easily penetrated the mat and heat transfer was accelerated. Numerous literature reports are coherent with that explanation (Humphrey and Bolton 1989; Bolton et al. 1989; Thoemen and Humphrey 2001). In addition, the recovered particles are partially densified material that exhibits higher heat conductivity (Kollmann 1955). Keeping in mind that moisture content in the recovered and industrial particles was comparable, the effect of that can be neglected.

The particleboards having in the core layer 80% of mixture IV, V and particleboards having in the core layer 100% of mixture III, IV and V (Fig. 4), exhibited a decrease in density between 6 and 23% in comparison to the reference (644 kg/m^3). It probably comes from the insufficient bonding of the PF-covered particles with UF resin within the core layer which resulted in a subsequently loosened structure and lower board density.

The thickness swelling (TS) tests revealed swelling comparable to the reference for particleboards with mixture I (8–10%). TS of boards that contained the mixtures II–V increased by 25–200% (Fig. 5). An even more severe effect was observed for the particleboards containing 100% of the mixture IV and V, where delamination occurred yet before sample soaking. According to EN 312 (2010) standard the required TS for the 16-mm thick P7-P3 type boards is 10–15%. Thus, it was shown that all the particleboards containing 100% of the particles with UF-resin and the particleboards containing up to 20% of the particles with PF-resin met the requirement.

It can be seen that the addition of the recovered particles affected the MOR of the boards (Fig. 6). The decrease ranged between 13 and 91% in comparison to the reference. The observation can be explained by the lower slenderness and flatness that rendered lower contact area between the particles (Arabi et al. 2011). The effect was especially apparent for the particleboards containing particles with PF-resin. It additionally suggests that alkaline character of the binder could inhibit UF curing (Czarnecki et al. 2003). An

Fig. 4 Density of the particleboards made of the recovered particles

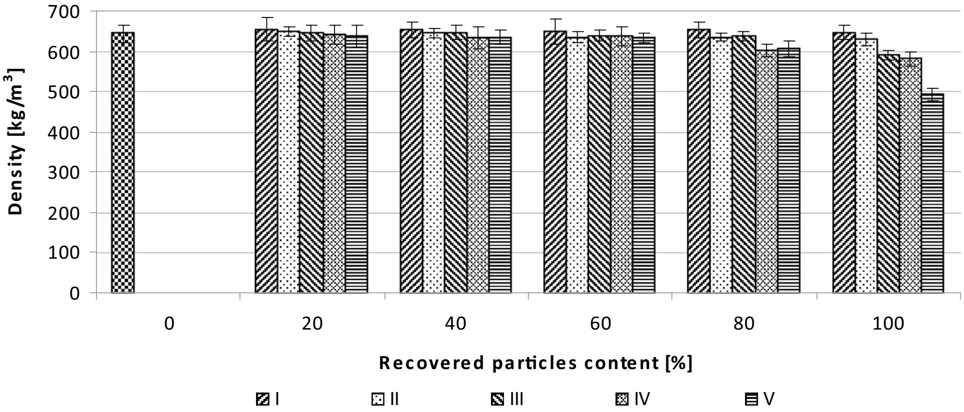
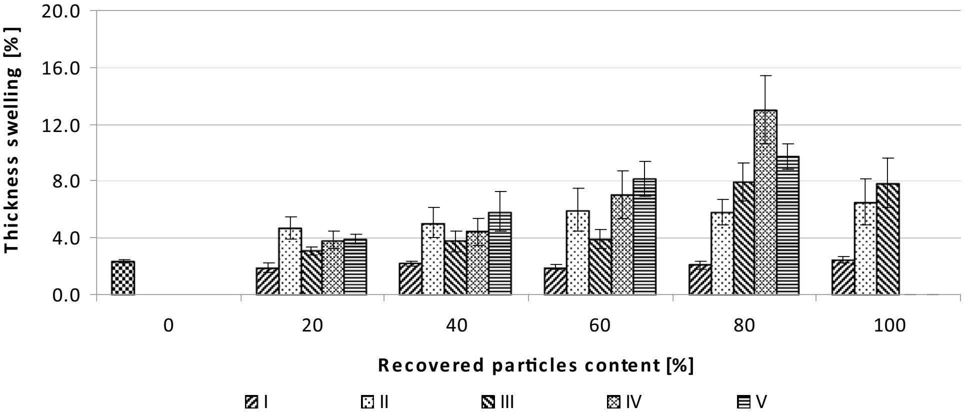


Fig. 5 Thickness swelling of the particleboards made of the recovered particles



increased MOR (16%) achieved for the boards containing 20% of the mixture I comes from more compact structure of the core layer provided by the recovered particles of smaller size. All the boards that contained particles with UF-resin and the boards bearing up to 40% of particles with PF-resin exhibited sufficient MOR to meet the requirements of the EN 312 standard. Thus, 40% addition of particles with PF-resin is a suggested upper limit for the recovered material.

Similar relations were found for MOE (Fig. 7). However, the results indicate that the effect of the particles with PF-resin on the decrease in MOE was apparent. The respective requirements of the EN 312 standard were met by the boards composed of 20–80% of mixture I, 20–60% of mixture II or III, and 20–40% of mixture IV. None of the boards bearing mixture V met the requirement.

When internal bonding (IB) is concerned, one can see that 20% addition of mixture I, II or III did not significantly affect the parameter (Fig. 8). Moreover, the higher the content of the particles with PF-resin was, the lower IB was observed. So that the respective EN 312 standard

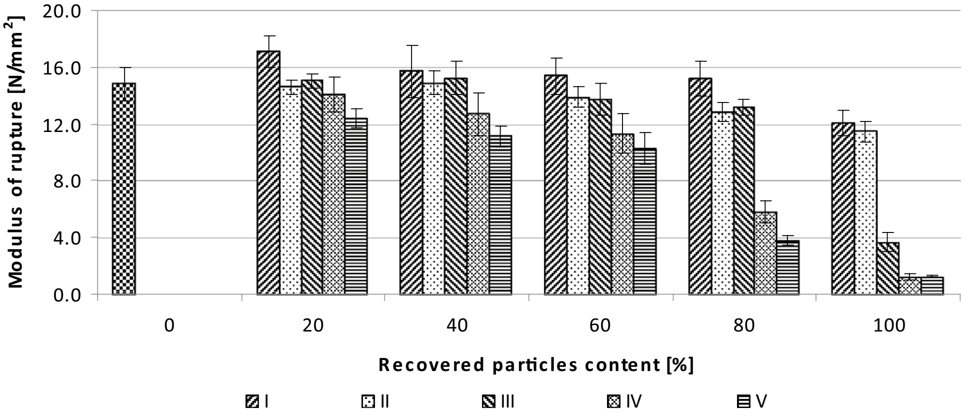


Fig. 6 Modulus of rupture of the particleboards made of the recovered particles

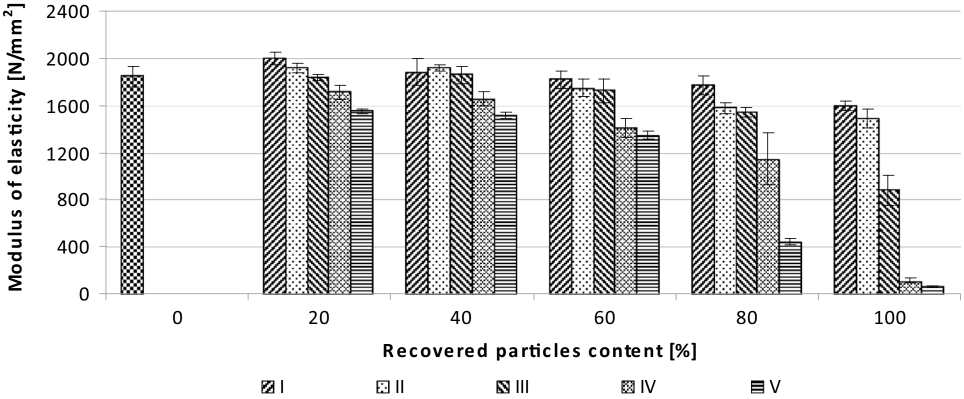


Fig. 7 Modulus of elasticity of the particleboards made of the recovered particles

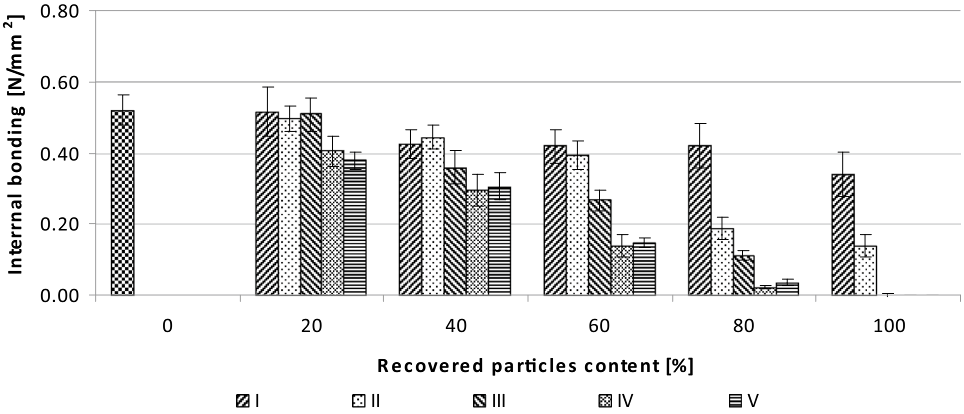


Fig. 8 Internal bonding of the particleboards made of the recovered particles

requirement (minimum IB 0.24 N/mm^2) was met only by the boards bearing 20–80% of mixture I, 20–60% of mixture II or III and 20–40% of mixture IV or V.

The observed effects are of complex and probably synergistic nature, so both the chemical properties of PF and UF adhesives as well as the size, anisotropy, porosity and wetting of woody material play important roles, too. The obtained results, in general, indicate the PF-covered particles to be poorly bondable material in comparison to the UF-covered ones. The explanation of UF curing inhibition remains in accordance with the report by Czarnecki et al. (2003). Lower bondability of the recovered particles can also be explained by their lower porosity caused by pre-densification and subsequently more difficult penetration and surface wetting for the liquid adhesive (Pocius 2002). Hence, the type of binder present in the recycled material and its chemical nature strongly affected the particles bondability and the final performance of the boards.

4 Conclusion

The obtained results indicate that the chemical nature of the binder (UF or PF) present in the waste plywood affected neither the shredding operation nor the characteristics of the produced particles. It was demonstrated that the particles obtained with a 14-mm mesh screen exhibited properties closest to those determined for the industrial particles.

It can also be concluded that waste plywood can be recycled in the form of particles for particleboard manufacturing. However, the type and amount of the recovered particles strongly influence the resultant properties of the produced particleboards. Eventually, the origin as well as chemical and physical properties of a recovered material recycled to production determines the quality and area of use of the product.

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