Evaluation of Mechanical and Physical Properties of Particleboards with the Core Layer Made from Willow (*Salix viminalis*)

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The objective of this study was to investigate some mechanical and physical properties of three-layer particleboards with the core layer made from various willow (*Salix viminalis*) and industrial pine wood particle mixtures. Increasing willow content slightly worsened the modulus of elasticity and modulus of rupture but improved internal bond, screw holding, water absorption, and thickness swelling. The effects of resin content in the core layer and the density of particleboards were also studied. Mechanical properties, especially modulus of elasticity and internal bond, of particleboards with willow particles met the requirements of EN 312 standard for boards of type P2. The willow (*Salix viminalis*) can be considered as a substitute for pine wood for the manufacturing of the core layer of three-layer particleboards.

Keywords: Particleboard; Core layer; Salix viminalis; Mechanical properties; Physical properties; Resin content; Density

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INTRODUCTION

Particleboards are the most commonly used wood composites for nonstructural applications, especially for furniture manufacturing. Increasing particleboard production in recent decades and limited forest resources has caused the need to look for alternative lignocellulosic materials. Particleboards are readily made from a variety of agricultural residues, such as kenaf stalks, cereal straw, and rice husks (Stark *et al.* 2009). They can be made from virtually any wood material. Research is still being carried out on the use of underutilized low-quality wooden materials for particleboard manufacturing (Nemli and Kalaycioglu 2001; Kalaycioglu *et al.* 2005; Zheng *et al.* 2006; Ashori and Nourbakhsh 2008; Lin *et al.* 2008). Another possible raw material can be fast-growing shrubs. Such a shrub being cultivated for energy purposes is the willow (*Salix viminalis* L.). In Poland it is cultivated in about 800 short-rotation plantations on an area of 6,160 ha (Grzybek 2011). Genetic and breeding studies have been conducted in Poland in order to provide a basis for the development of high-yielding willow cultivars, adapted to the different climatic and soil conditions in Poland (Stolarski *et al.* 2008; Jeżowski *et al.* 2011).

The feasibility of using the willow (*Salix viminalis*) as raw material for particleboard production has been studied by only a small number of researchers. Sean and Labrecque (2006) investigated the usefulness of Quebec clones of the willow (*Salix viminalis*). They studied three-layer particleboards with face and core layers containing from 10 to 30% willow, and concluded that the mechanical properties of particleboards with up to 30% willow particle content were generally greater than those of particleboards made from industrial wood particles. Frackowiak *et al.* (2008) showed that the replacement of 25% of industrial pine particles by willow ones in the core layer of three-layer particleboards improved their mechanical properties in bending. The authors of the mentioned papers did not explain the reason of improving the mechanical properties of particleboards by using willow particles instead of industrial ones.

Kowaluk *et al.* (2011) investigated the possibility of using non-standard, specially prepared, particles from the willow (*Salix viminalis*) to produce three-layer particleboards. These particles, named fibrous chips, were produced on a Pallmann defibrator using a span of 1.2 mm between the hammer and milling disc. They observed that the mechanical properties in bending of particleboards with fibrous chips were markedly higher than those of comparable particleboards made from industrial wood particles.

In a recent study on one-layer particleboards made from a mixture of willow (*Salix viminalis*) and industrial pine wood particles, Warmbier *et al.* (2013) found that increasing the willow content from 0 to 100% slightly worsened mechanical properties in bending, and improved internal bond, screw holding, water absorption, and thickness swelling of particleboards. The main reason of these phenomena was the geometry of the particles. The willow particles were shorter and wider in comparison to industrial wood particles.

The results of the above studies are inconsistent. The first three studies indicate that willow particles as a substitute for industrial particles improve the mechanical properties in bending while the fourth study indicates that those particles worsen them. Therefore, further investigation seems to be needed to explain the effect of willow on particleboard properties. It was assumed that willow particles as a substitute for industrial wood particles would be used for manufacturing only the core layer of three-layer particleboards. The objectives of this study were to evaluate some mechanical and physical properties of three-layer particleboards with the core layer made from mixture of willow and industrial wood particles as affected by various factors: (1) willow content, (2) resin content in the core layer, (3) particleboard density, and (4) to compare these properties with the requirements of EN 312 standard.

MATERIALS AND METHODS

Materials

Three-year-old stems of willow (*Salix viminalis*) were collected from the Miescisko plantation in the Wielkopolska Region of Poland. The stem diameter at the base ranged between 28 and 35 mm, while the height ranged between 4.9 and 5.3 m. The mean density of the stems was 513 kg/m^3 at a moisture content of 12%, and bark percentage was about 15% of stem weight. The stems were chipped in a laboratory hammer-mill. Industrial pine particles used for manufacturing the core layer of three-layer particleboards were supplied by Pfleiderer Prospan Wieruszow (Poland). Both willow and pine particles were then screened by an analytical sieve shaker using 4 mm and 1 mm sieves. Particles that passed through the 4 mm sieve and remained on the 1 mm sieve (Fig. 1) were used as furnishes for the core layer of experimental particleboards. The bulk densities of willow and pine particles were 203 and 169 kg/m^3, respectively.

The raw material for the face layers of experimental particleboards was industrial fine particles made from pine wood. Both the coarse particles for the core layer and the fine ones were dried in an air-circulation oven to achieve a moisture content of less than 3%. Urea-formaldehyde (UF) resin was used as a binder. It had a density of 1.26 g/cm^{3}at 60% solids, pH value of about 7, a viscosity of 400-600 MPa*s at 20 ^{o}C and gel time of 40 s at 100 ^{o}C. As a hardener, 35% ammonium chloride (NH4Cl) solution, which was 1% of the oven dry weight of particles, was used. No water-repelling agent was added to the particles.

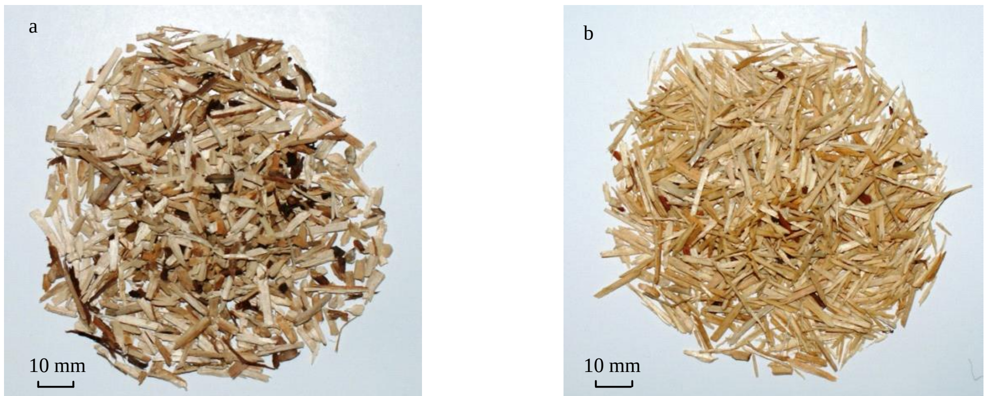

Fig. 1. Willow (a) and industrial pine (b)

Particleboard Preparation

Table 1. Experimental Design

Board type	Core layer composition (wt.%)		RC (%)	D (kg/m^3)
	willow particles	industrial wood particles		
A	0	100	8	660
B	50	50	8	660
C	100	0	8	660
D	0	100	9	660
E	50	50	9	660
F	100	0	9	660
G	0	100	8	700
H	50	50	8	700
I	100	0	8	700
J	0	100	9	700
K	50	50	9	700
L	100	0	9	700

Table 2. Manufacturing Parameters

Board thickness	16 mm
Board dimensions	40 cm x 40 cm
Shelling ratio*	35%
Resin content in face layers	10%
Press temperature	180^{o}C
Maximum pressure	2.5 MPa
Press closing time	30 s
Pressing time	5 min

*Shelling ratio = proportion (by oven-dry weight) of face layers.

Three variable factors were taken into account: willow particle content (WPC) in the core layer (0, 50, and 100%), resin content (RC) in the core layer (8 and 9%), and density (D) of particleboard (660 and 700 kg/m^3). The experimental design is shown in Table 1. The board manufacturing parameters are listed in Table 2. Four experimental boards were produced for each board type. The boards were not sanded.

Particle Geometry Characterization

For comparison purposes, the fraction analysis and the dimensions of willow and industrial pine wood particles used for the core layer were determined. The dimensions were measured for 300 randomly selected particles of each type, and length/thickness and width/thickness ratios were calculated to obtain particle geometric characteristics.

Testing Methods

Prior to testing all the boards were stored in controlled conditions (50% relative humidity and 20 ^{o}C) for two weeks. Test specimens were cut from the boards to determine the following mechanical and physical properties according to appropriate EN standards: modulus of elasticity (MOE) and modulus of rupture (MOR) (EN 310 1993), internal bond (IB) (EN 319 1993), screw-holding strength in a direction perpendicular (SH⊥) and parallel (SH||) to the board plane (EN 13446 2002) by using screws with a diameter of 3.5 mm, length of 45 mm and a hole diameter of 2.5 mm, and water absorption (WA) and thickness swelling (TS) after 24 h (EN 317 1993). Test specimens for IB, WA, and TS were prepared from the specimens that were formerly tested for MOE and MOR. Twenty replicates were run for each test.

Statistical Tests

The obtained data were statistically analyzed. Three-way analysis of variance (ANOVA) was conducted to determine the significance of the effects of WPC, RC, and D on the particleboard properties. Tukey's test was applied to evaluate the statistical significance between mean values of the properties of particleboards with different WPC.

RESULTS AND DISCUSSION

Particle Geometry

The fraction analysis of willow particles in comparison to industrial pine wood particles is presented in Table 3. Willow particles had a greater content of the fractions 4>F>3.15 and 3.15>F>2.5, and a smaller content of the fractions 2>F>1.6 and 1.6>F>1 than industrial wood particles. The content of the fraction 2.5>F>2 was similar for the compared particles.

The dimensions of willow and industrial pine wood particles as well as their length-to-thickness (slenderness) and width-to-thickness ratios are shown in Table 4. For both fraction groups of particles, 4>F>2.5 and 2.5>F>1, willow particles were shorter but thicker and wider than industrial wood particles. As a result, the slenderness of willow was considerably less than that of industrial wood particles, while the width-to-thickness ratio of both particles was similar.

The results of the ANOVA test are shown in Table 5. Both variables referring to the core layer of particleboard, WPC and RC, significantly affected the tested board properties.

Table 3. Fraction Analysis per Weight of Willow and Industrial Pine Wood Particles Used for the Core Layer

Screen hole size range (mm)	Willow particles (%)	Industrial wood particles (%)
4 > F > 3.15	14.9	10.3
3.15 > F > 2.5	22.1	12.9
2.5 > F > 2	25.5	26.1
2 > F > 1.6	17.2	24.0
1.6 > F > 1	20.3	26.7

Table 4. Dimensions, Length/Thickness and Width/Thickness Ratios of Willow and Industrial Pine Wood Particles

	Length (mm)		Width (mm)		Thickness (mm)		Length/thickness		Width/thickness	
	Willow particles	Industrial wood particles	Willow particles	Industrial wood particles	Willow particles	Industrial wood particles	Willow particles	Industrial wood particles	Willow particles	Industrial wood particles
4>F>2.5	12.5(3.1)	21.3(4.2)	3.1(0.6)	2.9(0.5)	1.4(0.5)	1.2(0.4)	9.9(4.4)	19.9(8.2)	2.8(0.9)	2.8(1.3)
2.5>F>1	15.1(2.5)	17.3(3.5)	1.8(0.4)	1.6(0.4)	0.9(0.2)	0.8(0.3)	17.4(6.6)	25.6(12.1)	2.2(0.7)	2.3(1.0)

Standard deviations in parentheses

ANOVA and Tukey's Analysis

Table 5. Three-way ANOVA Test on the Effects of WPC, RC and D on Particleboard Properties (p-values)

Variable	MOE	MOR	IB	SH ⊥	SH ‖	WA	TS
WPC	<0.0001*	<0.0001*	<0.0001*	0.4331^{ns}	0.0052*	0.0002*	<0.0001*
RC	<0.0001*	0.0015*	<0.0001*	0.0207*	0.0005*	<0.0001*	<0.0001*
D	<0.0001*	<0.0001*	0.2035^{ns}	0.0007*	0.4366^{ns}	<0.0001*	<0.0001*
WPC x RC	0.8010^{ns}	0.8047^{ns}	0.9386^{ns}	0.8503^{ns}	0.8620^{ns}	0.3599^{ns}	0.5381^{ns}
WPC x D	0.5075^{ns}	0.7650^{ns}	0.4393^{ns}	0.9526^{ns}	0.9930^{ns}	0.7898^{ns}	0.4192^{ns}
RC x D	0.0296*	0.5947^{ns}	0.0537^{ns}	0.4805^{ns}	0.4366^{ns}	0.0016*	0.0014*
WPC x RC x D	0.4520^{ns}	0.9160^{ns}	0.6483^{ns}	0.7964^{ns}	0.8945^{ns}	0.1298^{ns}	0.5451^{ns}

* Denotes significance at 0.01.
^{ns} Not significant at 0.05.

Table 6. Effect of WPC on Particleboard Properties for the Groups of Boards with Different RC and D

WPC (%)	MOE (GPa)	MOR (MPa)	IB (MPa)	SH ⊥ (MPa)	SH ‖ (MPa)	WA (%)	TS (%)
0	2.56^{c}	14.5^{c}	0.61^{a}	25.3^{a}	15.6^{a}	81.1^{b}	27.4^{b}
50	2.47^{b}	14.0^{b}	0.66^{b}	24.9^{a}	16.6^{b}	81.2^{b}	26.8^{ab}
100	2.33^{a}	13.1^{a}	0.68^{b}	24.8^{a}	16.7^{b}	78.1^{a}	26.0^{a}

Mean values with the same letter for given property were not significantly different at the 5% level.

The only exception was the effect of WPC on SH⊥. The variable D significantly affected the properties, with the exception of IB and SH||. In general, the interactions between the variables were not significant for the board properties.

The results of Tukey's test for board groups with different RC and D but with the same WPC are presented in Table 6. Mean values with the same letter for each property were not significantly different at the 5% level.

MOE and MOR

The results for MOE and MOR of particleboards as a function of WPC are presented in Fig. 2. These properties depended significantly on WPC (Table 5), and decreased with increasing WPC from 0 to 100%. This relation referred to boards with different RC and D. The decreases in MOE and MOR with increasing WPC from 50 to 100%, for the group of boards with different RC and D (Table 6), were on average 5.7% and 6.4%, respectively, and were greater than those with increasing WPC from 0 to 50% which were on average 3.5 and 3.4%.

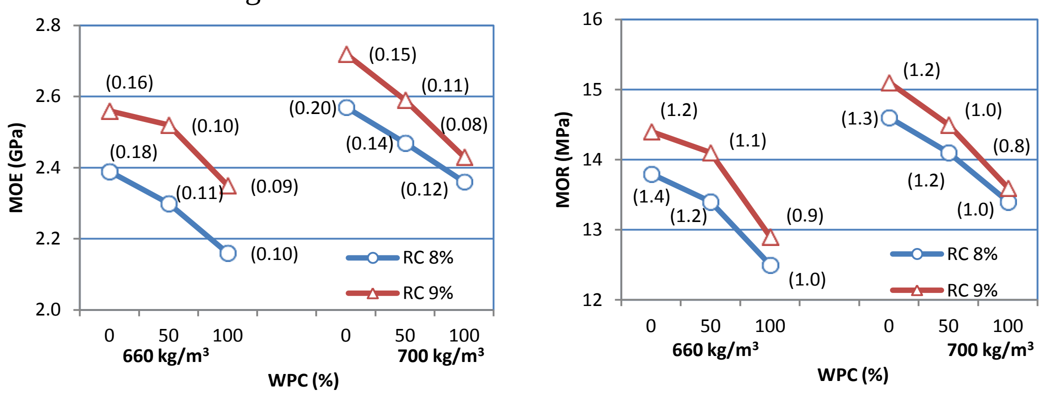

Fig. 2. Effect of WPC on MOE and MOR of particleboards with different RC and D (standard deviations in parentheses)

The negative effect of willow particles (WPs) in the core layer of particleboard on mechanical properties in bending was mainly caused by WP geometry. The slenderness (length/thickness) of WPs (Table 3) was much smaller in comparison to industrial wood particles. According to the theory of mechanics of fiber-reinforced composite, their mechanical properties in bending depend among other things on particle length and slenderness. The longer and more slender particles, especially the particles oriented in parallel to the axis of the bending specimen, the greater MOE and MOR of composite. This rule was confirmed for particleboards by Rackwitz (1963) and Arabi *et al.* (2011). A similar effect of WPC on MOE and MOR of one-layer particleboard made from WPs and industrial wood particles was observed by Warmbier *et al.* (2013). MOE and MOR of particleboards made from 100% WPs were smaller by 22.1 and 15.3%, respectively, than those of particleboards made from 100% industrial wood particles when the resin content was 10%, and smaller by 19.4 and 7.1%, respectively, when this content was 8%.

The effect of WPs in the core layer on MOE and MOR, although statistically significant, was slight. It was smaller than that for one-layer particleboard (Warmbier *et al.* 2013). This slight effect was a consequence of the fact that MOE and MOR of three-layer particleboard are dependent mainly on surface layers (Keylwerth 1958; Wilczyński and Kociszewski 2007; Wilczyński and Kociszewski 2012). In comparison with the core layer, the face layers, made of smaller particles with a higher RC, have a greater compaction ratio and density which result in better mechanical properties of particleboard. Face layers are crucially important in transferring load in elements made from particleboard. When these elements are loaded in bending, face layers transfer more than two thirds of the bending moment.

Another cause for the decrease of MOE and MOR with increasing WPC could be the usage of bark, which was considerably greater for WPs than for industrial wood particles. The mechanical properties of bark are worse than those of wood. Thus, the greater WPC, the worse were the particleboard properties. The deleterious effect of bark on MOE and MOR of three-layer particleboards with 22 and 30% usage of the WPs was found by Sean and Labrecque (2006). Zheng *et al.* (2006) concluded that MOE and MOR of particleboard from saline Athel wood decreased markedly as bark content increased from 0 to 16.2%.

MOE and MOR depended significantly on RC and D (Table 5), and increased with increasing RC and D (Fig. 2). The increases in MOE with increasing RC from 8 to 9% were on average 8.7 and 4.8% for boards with D of 660 and 700 kg/m^3, respectively. The increases in MOR with increasing RC were on average 4.1 and 2.7% for boards with D of 660 and 700 kg/m^3, respectively. MOE of boards with D of 700 kg/m^3 were on average by 8.1 and 4.3% greater than that of boards with D of 660 kg/m^3, respectively for boards with RC of 8 and 9%. MOR of boards with D of 700 kg/m^3 was on average 6.1 and 4.4% greater than that of boards with D of 660 kg/m^3, for boards with RC of 8 and 9%, respectively. These results can be explained by the fact that the increase in RC caused more uniform coating particle surface by adhesive, and moreover that the increase in D resulted in an increase in particle surface due to increasing wood compression (Rackwitz 1963). Similar effects of RC and/or D on MOE and MOR were found in other studies (Nemli and Kalaycioglu 2001; Kalaycioglu *et al.* 2005; Zheng *et al.* 2006; Ashori and Nourbakhsh 2008; Lin *et al*. 2008; Arabi *et al*. 2011; Guler and Buyuksari 2011; Kowaluk *et al.* 2011; Eslah *et al.* 2012; Warmbier *et al.* 2013).

IB and SH

The results for IB and SH of particleboards in relation to WPC are presented in Fig. 3. IB and SH|| depended on WPC whereas SH⊥ did not depend significantly (Table 5). Both IB and SH|| increased with increasing WPC from 0 to 100%. This relation referred to boards with different RC and D. The increases in IB and SH|| with increasing WPC for the group of boards with different RC and D (Table 6), were on average 11.5 and 7.1%, respectively.

The reason IB and SH|| increased with increasing WPC was that the slenderness of WPs was smaller than that of industrial wood particles. The core layer with shorter and less slender particles comprised fewer free areas (voids) between crossing particles so that IB and SH|| of particleboard were greater. This relation for IB was shown by Rackwitz (1963) and Maloney (1993). It should be noticed that the densities of the core layer made from WPs and of that made from pine particles were almost the same despite the fact that the bulk density of WPs (203 kg/m^3) was greater than that of pine particles (169 kg/m^3). The density profiles of particleboards with the core layer from WPs and that from pine particles were also similar. On the other hand IB and SH|| of particleboards with greater WPC should be smaller due to the deleterious effect of bark. However, the negative influence of bark was lower than the positive influence of WP geometry. A similar effect of WPC on IB for one-layer particleboard made from WPs and industrial wood particles was observed by Warmbier *et al.* (2013). The increase in IB of three-layer particleboards with increasing WPC from 10 to 30% was also observed by Sean and Labrecque (2006).

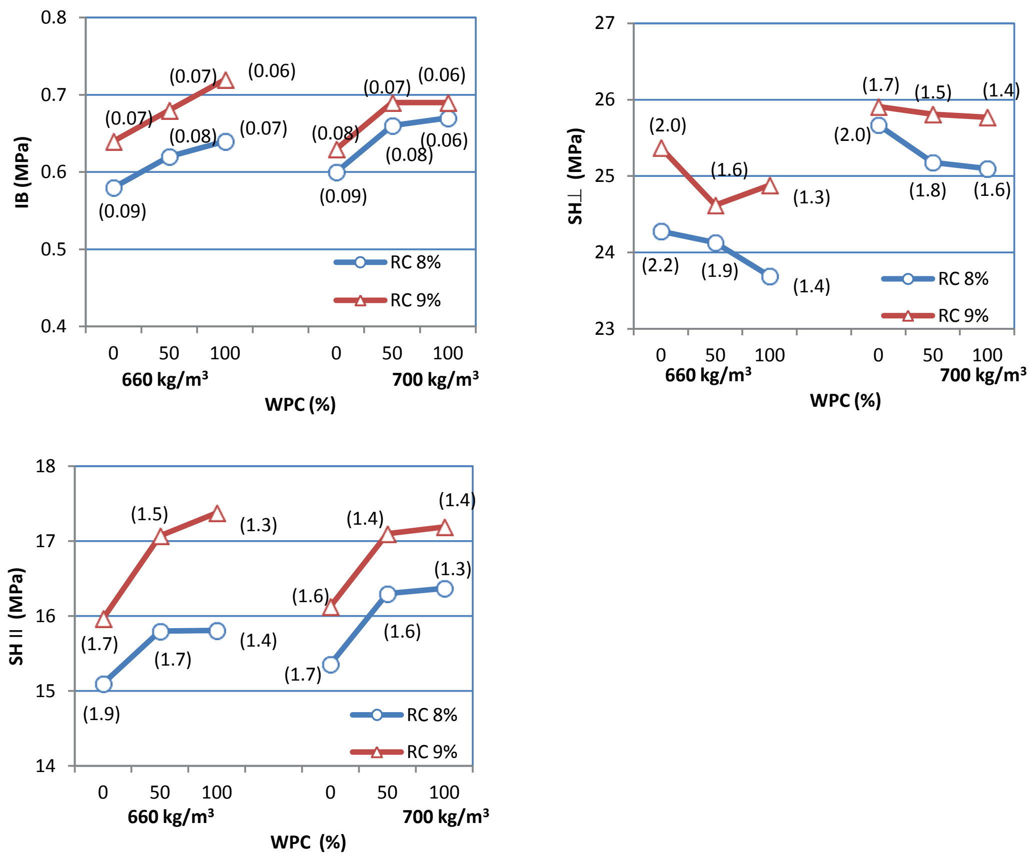

Fig. 3. Effect of WPC on IB, SH⊥, and SH‖ of particleboards with different RC and D (standard deviations in parentheses)

IB, SH‖, and SH⊥ depended significantly on RC (Table 5), and increased with increasing RC (Fig. 3). The increases in IB, SH‖, and SH⊥ with increasing RC from 8 to 9% were on average 7.5, 6.4, and 3.0%, respectively. The effect of D was significant only for SH⊥. With increasing D from 660 to 700 kg/m^3 SH⊥ increased on average by 4.1%. The explanation of these increasing properties as a function of increasing RC and D is the same as for MOE and MOR. Similar effects of RC and/or D on IB and/or SH were found in other studies (Nemli and Kalaycioglu 2001; Kalaycioglu *et al.* 2005; Zheng *et al.* 2006; Ashori and Nourbakhsh 2008; Lin *et al.* 2008; Arabi *et al.* 2011; Kowaluk *et al.* 2011; Eslah *et al.* 2012; Warmbier *et al.* 2013).

WA and TS

The results for WA and TS of particleboards as a function of WPC are presented in Fig. 4. These properties depended significantly on WPC (Table 5), and slightly decreased with increasing WPC from 0 to 100%. This relation referred to boards with different RC and D. The decreases in WA and TS with increasing WPC for the group of boards with different RC and D (Table 6) were on average 3.7 and 5.1%, respectively. The values of WA and TS were very high, varying from 72.0 to 85.9% for WA and from

22.8 to 29.9% for TS. This was due to not using water repelling agents in the board manufacturing.

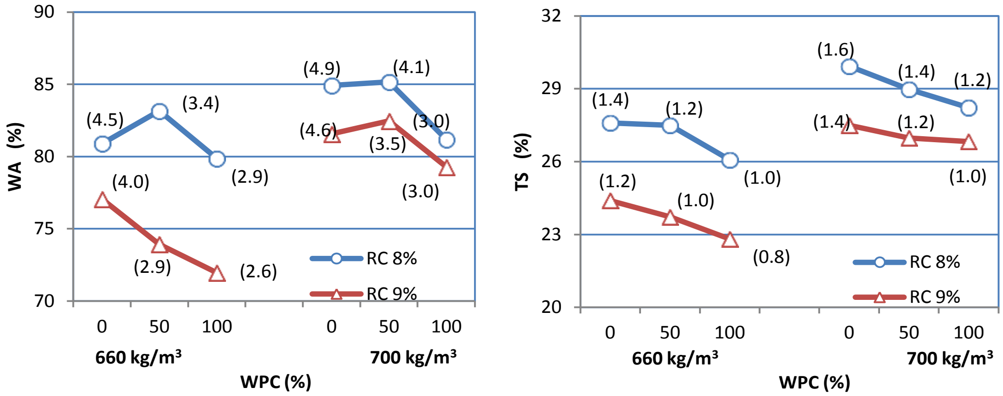

Fig. 4. Effect of WPC on WA and TS of particleboards with different RC and D (standard deviations in parentheses)

The decrease in WA and TS with increasing WPC is difficult to explain. WPs had higher bark content in comparison with industrial wood particles, and this should have resulted in increasing WA and TS (Zheng *et al.* 2006). In a previous study of one-layer particleboard made from WPs and industrial wood particles (Warmbier *et al*. 2013), a decrease in WA and TS with increasing WPC from 0 to 100% was also found. This decrease was even greater amounting to 7.1 and 11.1% for WA and TS, respectively.

WA and TS depended significantly on RC and D (Table 5). WA and TS decreased with increasing RC, and they increased with increasing D (Fig. 4). Increasing RC from 8 to 9% resulted in decreasing WA and TS on average by 5.8 and 9.7%, respectively. The positive effect of RC on the hygroscopic properties was mentioned in previous studies (Maloney 1993; Nemli and Kalaycioglu 2001; Ashori and Nourbakhsh 2008; Lin *et al.*2008; Warmbier *et al.* 2013). With increasing D from 660 to 700 kg/m^3, WA and TS increased on average by 5.5 and 11.1%, respectively. This was a result of the higher compression of wood particles and the smaller volume of free spaces between particles, which could be filled by swelling particles. This negative effect of D on WA and/or TS was also found in other studies (Maloney1993; Kalaycioglu *et al.* 2005; Warmbier *et al.* 2013).

Comparison to EN 312 requirements

The minimum property requirements for particleboards of a thickness of 16 mm, for use in dry conditions, according to EN 312 standard (2005) are listed in Table 7. MOE of produced particleboards with WPC of 50 and 100% varied from 2.30 to 2.59 GPa, and from 2.16 to 2.44 GPa, respectively. Therefore, all boards met the requirement for the board of type P2 (1.6 GPa). In addition, boards with WPC of 50%, and with WPC of 100%, excepting the board with RC of 8% and D of 660 kg/m^3, met the requirement for the board of type P4 (2.30 GPa).

MOR of particleboards containing 50 and 100% WPs ranged from 13.4 to 14.5 MPa and from 12.5 to 13.6 MPa, respectively. Thus, all boards met the requirement for the board of type P1 (11.5 MPa). Moreover, boards with WPC of 50%, and with WPC of 100% and D of 700 kg/m^3, met the requirement for the board of type P2 (13.0 GPa). IB of particleboards with WPs varied from 0.62 to 0.72 MPa, and considerably exceeded the requirement for the boards of type P2 and P4 (0.35 MPa). TS of particleboards with WPs ranged from 22.8 to 29.0% and did not meet the requirement for the board of type P4 (15.0%). As was mentioned, high values of TS were due to not using water repelling agents in the board manufacturing.

Table 7. MOE, MOR, IB, and TS Values Required by EN 312 for Boards for Use in Dry Conditions

Board type*	MOE (GPa)	MOR (MPa)	IB (MPa)	TS (%)
P1	-	11.5	0.24	-
P2	1.6	13.0	0.35	-
P4	2.3	15.0	0.35	15

* P1 = general purpose boards, P2 = boards for interior fitments,
P4 = load-bearing boards.

CONCLUSIONS

1. WPC in the core layer of three-layer experimental particleboards significantly affected almost all mechanical (MOE, MOR, IB, and SH||) and physical (WA and TS) properties of particleboards.
2. Increasing WPC from 0 to 100% slightly worsened MOE and MOR but improved IB, SH||, WA, and TS.
3. Increasing RC in the core layer from 8 to 9% significantly improved all determined properties.
4. Boards with higher D (700 kg/m^3) had better MOE, MOR, and SH⊥ but worse WA and TS than those with smaller D (660 kg/m^3).
5. MOE and IB of all boards with WPC of 50 and 100% considerably exceeded the requirements of EN 312 standard for the boards of type P2, whereas the requirement for MOR was met for all boards with WPC of 50% and for boards with WPC of 100% and D of 700 kg/m^3.
6. WPs can be considered as a substitute for industrial wood particles for manufacturing the core layer of three-layer particleboards of type P2.

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