Properties of Particleboards Made of Biocomponents from Fibrous Chips for FEM Modeling

Emil Archanowicz,* Grzegorz Kowaluk, Wojciech Niedziński, and Piotr Beer

The present paper aims to determine values of the modulus of elasticity (MOE) and modulus of rupture (MOR) of particleboards made from specially prepared particles from willow (*Salix viminalis* L.) and black locust (*Robinia pseudoacacia* L.) to enable formulation of an orthotropic material model for use in computer numerical simulations (FEM; finite element method). The mean densities of the panels were 600 and 660 kg·m^{-3} for the willow and black locust, respectively. The MOE was used to test entire particleboards as well as their individual layers. The willow and black locust particleboards were compared with commercially available particleboards that met the requirements of the EN 312 standard. The modulus of rupture (MOR) of the particleboards was also determined according to the requirements of the EN 312 standard. The commercial particleboards showed the effects of different manufacturing directions, which resulted in changes in properties. No influence from manufacturing direction was found for the laboratory-made experimental panels. The impact of the thickness of the face layer of the specimens on MOE was also investigated. These tests indicated that the 2.1-mm sample showed no detectable distortive impact from the core layer. The tests confirmed the impact of manufacturing direction on the MOE of the commercial panels, which moreover was higher for the face layer. The highest MOE was found for the commercial panels, although the experimental panels met the requirements of the EN 312 standard, excluding the black locust at a mean density of 600 kg·m^{-3}.

Keywords: Particleboard; Modulus of elasticity (MOE); Modulus of rupture (MOR); Core layer; Face layer; Willow; Black locust; FEM modeling

*Contact information: Faculty of Wood Technology, Warsaw University of Life Sciences – SGGW, Nowoursynowska Str. 159, 02-776 Warsaw, Poland; *Corresponding author: emil_archanowicz@sggw.pl*

INTRODUCTION

The management of forest resources, and especially that of timber, has become the subject of worldwide discussion. To save both exotic and European species of trees, and because of wood deficits, research institutes have been investigating the possibilities of using small-dimension wood or non-wood materials in manufacturing experimental particleboard. The proper application of technology may enable various forest and agricultural products to be used as raw materials in particleboard manufacturing (Kalaycıoglu and Nemli 2006). Zheng *et al.* (2006) used a plant of the Tamaricaceae family (*Tamarix aphylla* L.), Pan *et al.* (2007) used saline eucalyptus (*Eucalyptus cinerea* Benth.), and Kalaycıoglu and Nemli (2006) used kenaf (*Hibiscus cannabinus* L.), an African annually planted crop. Another research trend to be noted is the use of various waste products in manufacturing engineered wood. Guler *et al.* (2008) utilised peanut hull (*Arachis hypogea* L.) mixed with the wood of black pine (*Pinus nigra* Arn.). Other researchers have studied the introduction of such plants as hemp, kenaf, sunflower, maize, topinambour, straw, sugarcane bagasse, bamboo, waste tea leaves, stalks and carpels of cotton shrubs, hazelnut shell (Guler *et al.* 2008), and kiwi prunings (Nemli *et al.* 2003).

Wong *et al.* (1999) examined the fundamental relationship between the density profile and the board properties such as modulus of rupture (MOR), modulus of elasticity (MOE), and internal bond (IB) of particleboard. They fabricated homo-profile particleboards made from *Shorea* spp, bonded with isocyanate resin. Wilczyński and Kociszewski (2007) determined MOR and MOE of medium density fiberboard (MDF) for three directions: the direction of the mat forming, the direction perpendicular to it, and the direction perpendicular to the panel plane. Wilczyński and Kociszewski (2012) investigated the elastic properties of the face and core layers of commercial three-layer particleboard. They used a method of compressing the block of specimens glued from strips of layers separated from boards.

Considerable further research, however, will be required before such materials are introduced into the mass production of boards. Moreover, in Europe these materials cannot provide a sufficiently wide resource base. Research has therefore been carried out recently on the use of fast growing energy crops, chiefly willow (*Salix viminalis* L.) and black locust (*Robinia pseudoacacia* L.). Kowaluk *et al.* (2011) tested the mechanical properties and application possibilities of experimentally engineered wood products made from the above materials. The test results confirmed the possibility of applying such particleboards in furniture manufacturing. Wilczyński *et al.* (2011) and Warmbier *et al.* (2010) tested the physical properties of three-layer experimental particleboards containing faces made of willow (*Salix viminalis* L.). However, the properties of boards made wholly of fast growing crops are still unknown; in particular, the properties of the individual layers of such boards remain to be investigated. An understanding of these properties is of great importance to furniture manufacturing.

The orthotropic character of particleboard (Fig. 1) is related to its manufacturing process. The continuous manufacturing process of industrially produced particleboard results in variations in its mechanical properties along and across the direction of manufacturing (Wilczyński and Kociszewski 2012). In the case of laboratory-made particleboard, there is no direction of manufacturing; consequently, no differences of direction along the board's plane will need to be taken into consideration.

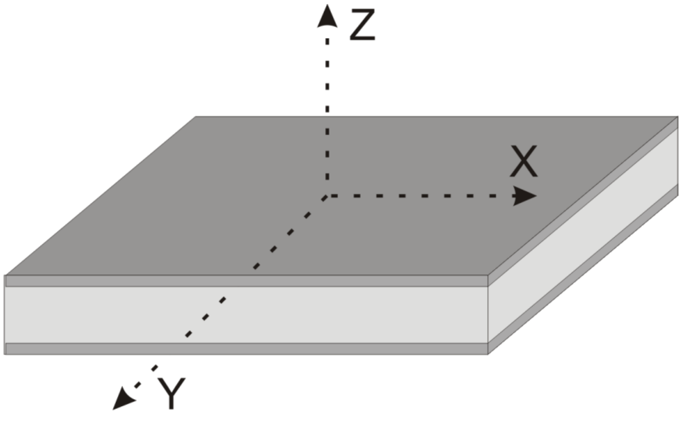

Fig. 1. Orthotropy of three-layer particleboard. X – particleboard manufacturing direction; Y – perpendicular to particleboard manufacturing direction; Z – perpendicular to the board plane

The research aim of this work was to determine empirically such values as the modulus of elasticity (MOE) and modulus of rupture (MOR) of entire particleboards and their individual layers. The test materials included experimental boards made of fibrous chips. Fibrous chips are obtained in a process similar to that of defibration in particleboard manufacturing. The values obtained for the experimental boards were compared with those obtained for commercial boards. The resultant values of the elasticity modulus will serve the purpose of preparing material models to be used in numerical simulations (FEM).

EXPERIMENTAL

The following materials were used in this research: 3-layer, 16-mm-thick, commercially available particleboard of the P2 type (according to EN 312 standard), with a mean density of 600 $kg \cdot m^{-3}$, hereinafter referred to as I600; 3-layer, 16-mm-thick particleboard made of fibrous chips from willow (*Salix viminalis* L.) with densities of 600 and 660 $kg \cdot m^{-3}$, hereinafter referred to as W600 and W660, respectively; and 3-layer, 16-mm-thick particleboard made of fibrous chips from black locust (*Robinia pseudoacacia* L.) with densities of 600 and 660 $kg \cdot m^{-3}$, hereinafter referred to as R600 and R660, respectively. The particleboard manufacturing process was explained in the paper Kowaluk *et al.* (2011).

The willow and black locust particleboards were laboratory-made, and therefore differences between the X and Y directions were not considered, as it was considered unlikely that such differences would occur in the manufacturing process of industrially produced particleboard. Such differences in commercial particleboard may result, among other causes, from manufacture on a continuous press, where the direction of manufacturing may be identified.

The particleboard density profiles were measured using a GreCon Dax-5000 laboratory density analyser. Samples whose dimensions met the technical requirements of the density analyser (50 x 50 mm) were measured to an accuracy of 0.01 mm and then weighed on laboratory scales to an accuracy of 0.01 g. The measurement speed was set at 0.05 mm/s, with 0.02-mm spacing between the measuring points.

The obtained density profile did not allow for the establishment of precise borders between the faces and the core. Consequently, three potential face sample thicknesses were used for testing, the first determined on the basis of the board’s mean density, and the second and third based on the mean increased or diminished by 10%, respectively (Fig. 2).

The moisture of the particleboards was determined using the gravimetric method. Three samples from each particleboard, sized 50 x 50 x 16 mm, were tested. The samples were weighed on laboratory scales to an accuracy of 0.01 g. They were then dried in a laboratory oven at 100 °C for a minimum of 12 h. Afterwards, they were reweighed. The moisture contents of the boards were as follows: I600, 5.3%; W660, 4.9%; W600, 5.4%; R660, 4.5%; and R600, 4.5%.

The modulus of elasticity and MOR tests were carried out on an Instron 3365 universal testing machine in accordance with the PN-EN 310 standard (Fig. 3).

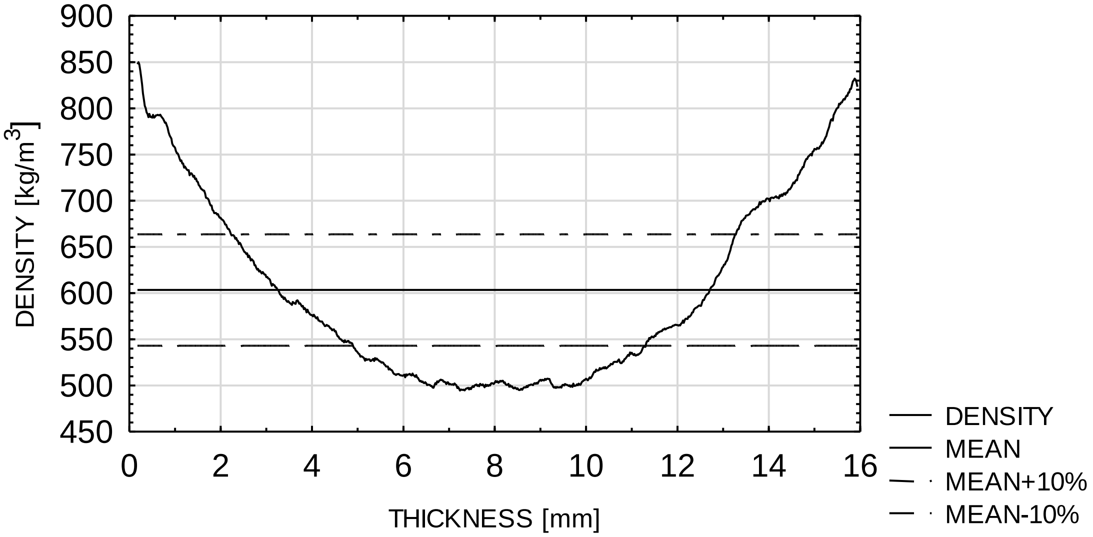

Fig. 2. Scheme of establishing potential borders between the layers

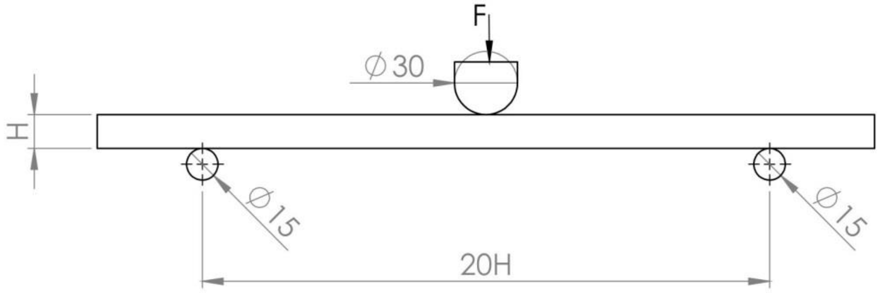

Fig. 3. Conditions for testing modulus of elasticity and MOR

The dimensions of the test samples are shown in Fig. 3. The crosshead speed was set in accordance with standards that require the destruction to occur after 60±30 s. Consequently, the crosshead speed was 7 mm/min for the entire board in the X and Y directions, 5 mm/min for the core layer in X and Y directions, and 2.5 mm/min for the face layer in the X and Y directions. For each test series, a linear regression was calculated for the linear range of the deflection force diagram. The linear regression was the basis for calculating the modulus of elasticity (MOE), given in Eq. 1, and the MOR, given in Eq. 2,

$$E_m = \frac{l^3(F_2 - F_1)}{4bt^3(a_2 - a_1)} \tag{1}$$

where l = support spacing, F_1 = force at 10% destructive force, F_2 = force at 40% destructive force, a_1 = deflection at force F_1, a_2 = deflection at F_2, b = sample width, and t = sample thickness,

$$\sigma_{MAX} = \frac{3 * F_{MAX} * l}{2bt^2} \tag{2}$$

where F_{MAX} = destructive force, l = support spacing, b = sample width, and t = sample thickness.

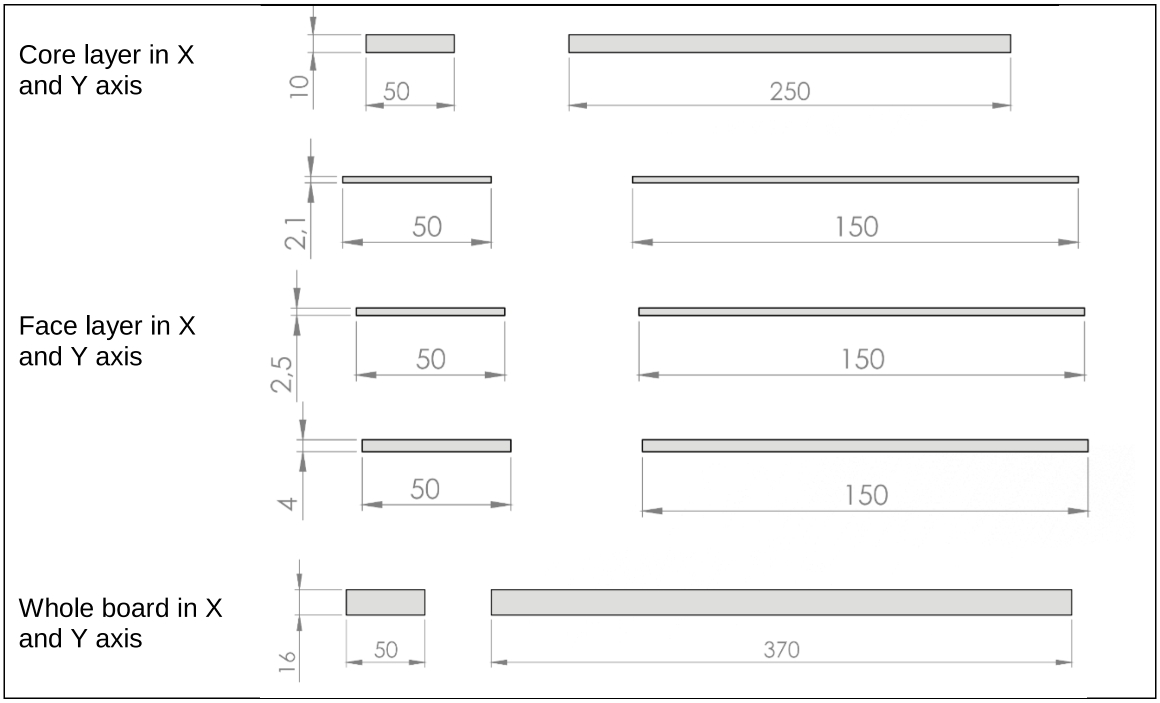

Fig. 4. Dimensions of the samples tested

RESULTS AND DISCUSSION

Initial Tests

The initial tests investigated the impact of face thickness on the value of MOE in the X and Y directions. The test objects were samples of willow and black locust particleboard of three nominal thicknesses each, 4.0 mm, 2.5 mm, and 2.1 mm. The results of the MOE tests are presented in Fig. 4. The biggest difference was found between the samples of thicknesses 2.5 mm and 2.1 mm, despite the smaller difference in thickness between these same samples compared to that between the 4.0-mm and 2.5-mm samples. No material difference between the species was identified. A trend that may be observed here is that particleboards of higher density showed a higher impact of layer thickness on the MOE.

A substitute MOE for three-layer particleboard may be calculated using the Smardzewski general correlation [4], based on the mechanics of the bending of beams (Smardzewski 2004),

$$E_Z J_Z = \sum_{I=1}^{n} E_I J_I \tag{3}$$

where E_Z = substitute MOE, J_Z = substitute moment of inertia, E_I = MOE of layers, and J_I = moment of inertia for layers.

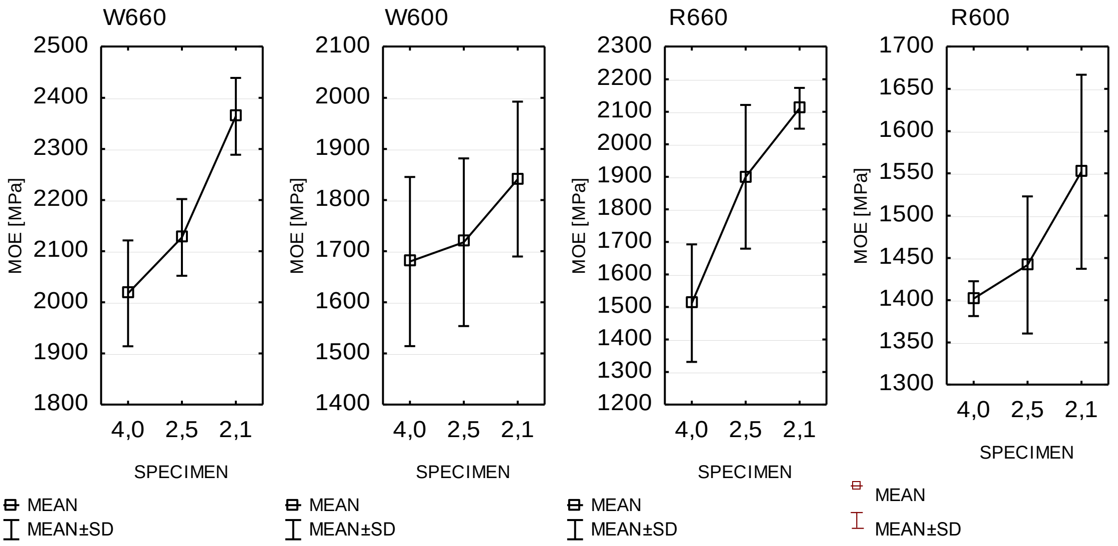

Fig. 5. Impact of sample thickness on the value of face MOE for willow and black locust particleboards

Correlation 4 was obtained by substituting the properties of particleboard layers,

$$E_Z J_Z = 2 * E_{ZW}(4h_{ZW}^3 + 3h_{ZW}h_W h_Z) + E_W h_W^3 \tag{4}$$

where E_Z = substitute MOE, E_{ZW} = face MOE, E_W = core MOE, J_{ZW} = face moment of inertia, J_Z = face substitute moment of inertia, J_W = core moment of inertia, h_Z = total board thickness, h_{ZW} = face thickness, and h_W = core thickness.

The Smardzewski correlation 4 was used in calculating the substitute MOE for the entire board. The values obtained for the face layer experimental board samples of 4 mm, 2.5 mm, and 2.1 mm were substituted for the face MOE (E_{ZW}), and the test values obtained for the core layer samples of these boards were substituted for the core MOE (E_W). The resultant substitute MOE was compared with the experimental value obtained for the entire board. The outcome was used as the criterion for choosing sample thicknesses for further tests. For instance, the outcome for W600 was as follows: 1626 MPa for the 4-mm sample, 1651 MPa for the 2.5-mm sample, 1735 MPa for the 2.1-mm sample, and 1779 MPa as the tested value for the entire board. The MOE values produced from calculations based on MOE for the 2.1-mm face sample and for the core showed statistically not significant differences in comparison with the experimental values of MOE for the entire board in all boards tested. As a result of these initial tests, the face sample thickness for numerical simulation was assumed to be 2.1 mm. The samples of 4.0 mm or 2.5 mm could not have represented the correct results, as the values of substitute MOE calculated on their bases diverged considerably from the experimental results.

The use of theoretical face thickness corresponding only with the density profile carried the risk of the core having an impact on the test results. In designing the experiment, it was necessary to take into consideration the manufacturing inaccuracy of the samples. Assuming an accuracy of 0.1 mm in the manufacture of the 2.5-mm samples, it was possible that certain samples measured 2.6 mm thick and could include the core. In accordance with the moment of inertia of the rectangular cross-section, the sample thickness in bending followed a third power law. It was therefore necessary to introduce negative dimensional tolerance to be absolutely sure that the samples would not contain the core. The results indicated that the data recorded for the 2.1-mm samples were correct and not distorted by the impact of the core layer.

Commercial Particleboard

As expected, the results showed that the MOE depended on the particleboard's direction of manufacturing (Fig. 6). The direction of manufacturing had the strongest impact on the face layer, with a statistically significant difference of 12%. The entire board showed a smaller difference of 8%, which was also statistically significant. The core layer difference, 1.5%, was statistically not significant. The 10% difference that was found for the 5-mm core layer was, as expected, statistically not significant.

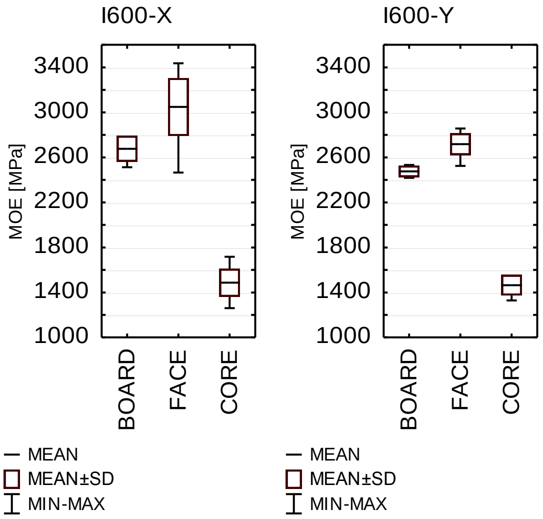

Fig. 6. MOE values for commercial particleboard in X and Y direction

The application of the Smardzewski correlation (Smardzewski 2004) found a similar correlation for the P2 boards, in which the biggest difference was also related to the MOE of the face layers: E_X = 3850 MPa and E_Y = 3301 MPa. The difference was less material for the core: E_X = 1030 MPa and E_Y = 883 MPa. The MOE value of the entire board was at a similar level: E_X = 2616 MPa and E_Y = 2243 MPa. The differences in the MOE values of the face layers and the core in comparison with those obtained experimentally are related to the differences in the density profiles of the boards. Using the Smardzewski correlation, the face layers were found to have a higher MOE at the expense of the lower MOE of the core layers; however, the MOE of each entire board was analogous to that of the boards tested. Wilczyński and Kociszewski (2012) investigated the value of the MOE of P4 boards. The boards also showed differences between the X and Y directions for face layers: E_X = 4480 MPa, and E_Y = 3760 MPa, and, as in the case of the Smardzewski results and the present research, a smaller difference for the core: E_X = 1820 MPa, and E_Y = 1470 MPa.

The test results was compared for the entire boards and for their individual layers with those calculated in accordance with the correlation 4 (Smardzewski 2008): Test value of E_X = 3046 MPa, E_Y = 2645 MPa calculated value of E_X = 3090 MPa,

E_X = 2619 MPa. Considerable convergence may be observed between the values of the face MOE obtained by the test and those obtained analytically on the basis of the experimental values of the modulus of elasticity for the entire board and the core using the Smardzewski correlation 4.

Table 1. MOR for Commercial Particleboard in MPa (σ_{MAX})

Direction	σ_{MAX}±SD		
	Board	Face	Core
X	13.2±1.2	19.4±0.9	7.8±0.2
Y	13.1±0.5	16.6±0.9	7.2±0.3

The values of MOR for the entire board meet the requirements of the PN-EN 312 standard, 13 MPa for P2 boards. The strength of the face layers amounted to 130 to 150% of the entire board's strength, as expected. The core strength fell to 65 to 70% of the entire board, as likewise expected.

Experimental Particleboards Composed of Willow and Black Locust

The willow boards met the requirements of the PN-EN 312 standard for P2 boards with regard to MOE and MOR (Fig. 7). The face MOE corresponded to 105% of the modulus of the entire board and to 85% of the modulus of the core.

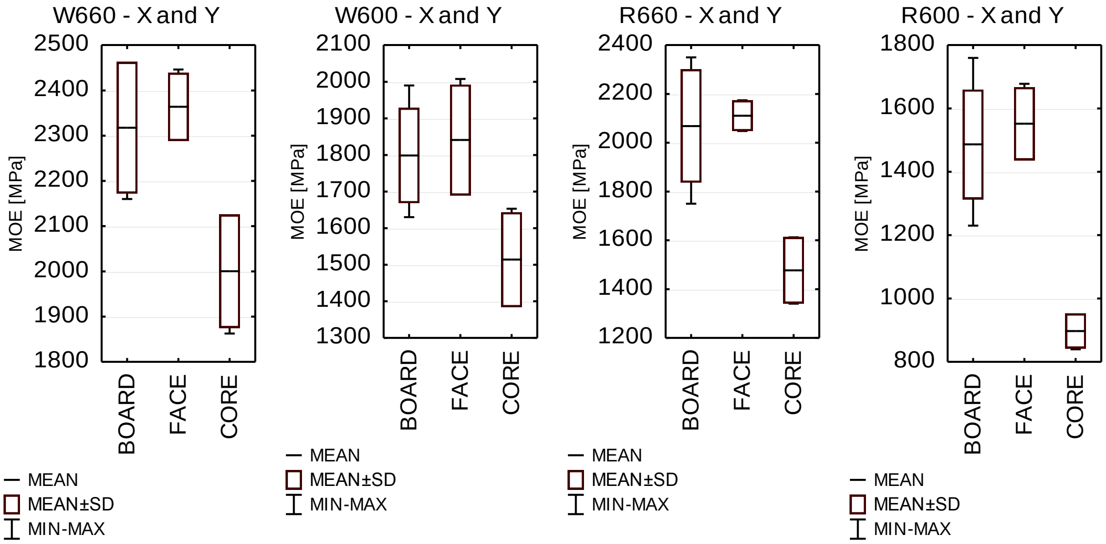

Fig. 7. MOE values for willow (W660, W600) and black locust (R660, R600) particleboards in three directions (X=Y)

The difference was smaller than it was for the P2 commercial particleboard, which may also be explained by the smaller difference in density between the face layers and the core in the experimental boards. The R660 boards met the PN-EN 312 standard with regard to MOE and MOR. The MOE of the face layer corresponded to 109% of the modulus of the entire board and to 72% of that of the core layer. The R600 boards did not meet the requirements of the PN-EN 312 standard with regard to MOE; they did, however, meet the standard with regard to MOR. The MOE of the face layer corresponded to 113% of the modulus of the entire board and to 68% of that of the core layer. This difference was similar to that found in the P2 commercial particleboard. It was, however, bigger than that found in the willow particleboards. This distinction between the R600 boards and the willow boards was attributed to the higher density of the black locust wood than that of willow, which resulted in a lower degree of compression in the case of the black locust boards.

The experimental results obtained for the entire boards and for their individual layers are compared with the values calculated in accordance with correlation [4], following the work of Smardzewski (2008). Test values were as follows: $E_{W660} = 2364$ MPa, $E_{W600} = 1841$ MPa, $E_{R660} = 2111$ MPa, $E_{R600} = 1552$ MPa. The corresponding calculated values were as follows: $E_{W660} = 2363$ MPa, $E_{W600} = 1840$ MPa, $E_{R660} = 2154$ MPa, $E_{R600} = 1571$ MPa. High convergence was observable between the experimental values of the face MOE and the values obtained analytically using the experimental values of the MOE for the core layer and for the entire board in accordance with the Smardzewski correlation 4.

Table 2. MOR Values for W660, W600, R660, and R600

Board Type	σ_{MAX}±SD		
	Board	Face	Core
W660	15.4±1.9	26.3±0.7	13.2±1.0
W600	13.3±1.2	16.5±0.8	8.4±0.9
R660	13.7±1.9	21.5±1.1	8.8±0.2
R600	9.6±1.0	16.4±0.6	4.3±0.2

The willow and black locust (except for R600) particleboards showed greater MOR values than did the commercial particleboards (I600). Only the R600 boards showed lower strength and did not meet the requirements of the PN-EN 312 standard. The greater strength may be explained by the difference in chip geometry between the experimental and commercial particleboards. This was most visible in direction Z, where the strength of W660 was considerably higher than that of I600.

Material Constants for Orthotropic Material Model to be used in Numerical Simulations

The test results enabled the construction of linear material models to be used in numerical simulations based on Hooke's law for orthotropic materials. The value of the Poisson ratio for all the boards was drawn from literature on the basis of research carried out by Smardzewski (2004, 2008) and Wilczyński and Kociszewski (2012). The Kirchhoff modulus was calculated on the basis of the well-known correlation 5, with the values of relevant orthotropy directions substituted for *E* and *v*.

$$G_{ij} = \frac{E_i}{2 * (1 + v_{ij})}, \qquad i,j = x,y, \qquad i \neq j \tag{5}$$

A set of material constants for the materials tested, for three layers, was thus obtained.

Table 3. Material Constants for Three-Layer Material Model of Particleboard for FEM

	Face					**Core**				
	I600	**W660**	**W600**	**R660**	**R600**	**I600**	**W660**	**W600**	**R660**	**R600**
E_X	3050	2360	1840	2110	1550	1490	2000	1510	1480	898
E_Y	2720	2360	1840	2110	1550	1460	2000	1510	1480	898
E_Z*	330	330	330	330	330	60	60	60	60	60
v_{YX}*	0.206	0.206	0.206	0.206	0.206	0.249	0.249	0.249	0.249	0.249
v_{ZX}*	0.040	0.206	0.206	0.206	0.206	0.041	0.249	0.249	0.249	0.249
v_{ZY}*	0.045	0.045	0.045	0.045	0.045	0.049	0.049	0.049	0.049	0.049
G_{XY}	1220	860	670	768	565	562	750	567	554	160
G_{XZ}	990	860	670	768	565	549	750	567	554	160
G_{YZ}	160	860	670	768	565	66	750	567	554	160
* - values was taken from Wilczyński and Kociszewski, (2007, 2011, 2012)										

Table 4. Material Constants for Entire Board for FEM

	I600	**W660**	**W600**	**R660**	**R600**
E_X	2680	2320	1780	2070	1490
E_Y	2480	2320	1780	2070	1490
E_Z*	115	115	115	115	115
v_{YX}*	0.282	0.282	0.282	0.282	0.282
v_{ZX}*	0.023	0.282	0.282	0.282	0.282
v_{ZY}*	0.043	0.043	0.043	0.043	0.043
G_{XY}	1110	904	694	807	580
G_{XZ}	965	904	694	807	580
G_{YZ}	72	904	694	807	580
* - values was taken from Wilczyński and Kociszewski (2007, 2011, 2012)					

The above material constants are the basis for orthotropic material models for numerical simulations in such programs as SolidWorks Simulation, Ansys, and Abaqus. They will serve the purpose of the numerical modeling of joints using commercial particleboards and particleboards made of fibrous chips.

CONCLUSIONS

1. It is possible to indirectly and directly test the MOE of the face layer of particleboard, directly by bending the 2.1-mm face samples and indirectly by bending the samples of the entire board and the core layer and then calculating the MOE analytically.
2. The mechanical properties, MOR and MOE of the particleboards manufactured from willow and black locust (except R600), meet requirements of the standard for particleboard production.
3. The particleboards from willow and black locust (except R600) can be successfully used for furniture production purposes.
4. This research has enabled three-layer material models and single layer material-model of the tested particleboards to be prepared for use in numerical simulations (FEM).

REFERENCES CITED

Guler, C., Copur, Y., and Tascioglu, C. (2008). "The manufacture of particleboards using mixture of peanut hull (*Arachis hypogaea* L.) and European black pine (*Pinus nigra* Arnold) wood chips," *Bioresource Technology 99*(8), 2893-2897.

Kalaycıoglu, H., and Nemli, G. (2006). "Producing composite particleboard from kenaf (*Hibiscus cannabinus* L.) stalks," *Industrial Crops and Products* 24(2), 177-180.

Kowaluk, G., Fuczek, D., Beer, P., and Grześkiewicz, M. (2011). "Influence of the raw materials and production parameters on chosen standards properties for furniture panels of biocomponents from fibrous chips," *BioResources* 6(3), 3004-3018.

Nemli, G., Hüseyin, K., Serdar, B., and Ay, N. (2003). "Suitability of kiwi (*Actinidia sinensis* Planch.) prunings for particleboard manufacturing," *Industrial Crops and Products* 17(1), 39-46.

Pan, Z., Zheng, Y., Zhang, R., and Jenkins, B. M. (2007). "Physical properties of thin particleboard made from saline eucalyptus," *Industrial Crops and Products* 26(2), 185-194.

Smardzewski, J. (2004). "Stereo mechanics of eccentric joint," in: *Modelling of Semi-Rigid Joints of Furniture Constructions*, B. Branowski and P. Pohl (eds.), Wyd AR, Poznań.

Smardzewski, J. (2008). *Projektowanie Mebli*. Poznań: PWRiL [In Polish].

Warmbier, K., Wilczyński, A., and Danecki, L. (2010). "Particle size dependent properties of three-layer particleboards with the core layer made from willow (*Salix viminalis*)," *Ann. WULS - SGGW, For. and Wood Technol* 72, 405-409.

Wilczyński, A., and Kociszewski, M. (2007). "Bending properties of particleboard and MDF layers," *Holzforschung* 61(6), 717-722.

Wilczyński, A., and Kociszewski, M. (2011). "Determination of elastic constants of particleboard layers by compressing glued layer specimens," *Wood Research* 56(1), 2-17.

Wilczyński, A., and Kociszewski, M. (2012). "Elastic properties of the layers of three-layer particleboards," *European Journal of Wood and Wood Products* 70(1-3), 357-359.

Wilczyński, A., Warmbier, K., and Danecki, L. (2011). "Properties of experimental particleboards with the core layer made from willow (*Salix viminalis*)," *Ann. WULS - SGGW, For. Wood Technol.* 76, 194-198.

Wong, E., Zhang, M., Wang, Q., and Kawai, S. (1999). "Formation of the density profile and its effects on the properties of particleboard," *Wood Science and Technology* 33, 327-340.

Zheng, Y., Pan, Z., Zhang, R., Jenkins, B. M., and Blunk, S. (2006). "Properties of medium-density particleboard from saline Athel wood," *Industrial Crops and Products* 23(3), 318-326.

Article submitted: June 26, 2013; Peer review completed: August 5, 2013; Revised version received and accepted: October 8, 2013; Published: October 16, 2013.