Newly Developed Boards Made from Crushed Rapeseed Stalk and their Bendability Properties

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The bendability of a material can be classified as both a positive and negative characteristic. The classification depends on the intended use of the given material. In the case of materials intended for bending (solid wood), this property is positive; whereas in the case of building materials this property may have a negative effect on the stability and durability of the finished structure. Depending on the use of the material, different characteristics of bendability can be used to describe it. The important characteristics include the force and deflection at the limit of proportionality and at the modulus of rupture. Because the bendability also depends on the material thickness, this characteristic is most often expressed as the ratio of the material thickness to the smallest achievable bent radius. Therefore, an analysis of the minimum curve radius and coefficient of bendability was performed. The bending characteristics were measured for composite materials, which were made of crushed rapeseed stalk and bonded with powder polyester adhesive. The stalks were subjected to different modifications (R, H_2O, and NaOH). The results of this work indicated that rapeseed is a prospective raw material for the production of composite materials with specific properties.

Keywords: Bendability; Modulus of elasticity; Limit of proportionality; Elastic potential; Composite material

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INTRODUCTION

The bendability of a material can be seen as both a positive and negative factor (Požgaj *et al.* 1997; Gaff 2014; Gaff *et al.* 2017b), depending on its specific purpose. While material deflection is undesirable in the construction of conventional furniture, such as table tops and cabinet shelves, it can be desirable in selected applications and certain design elements, and is even indispensable in some cases. The technology for producing bentwood furniture, such as chairs and armchairs, has been used for decades. Larger interior units with spatially wavy and curved elements cause trouble for designers and furniture manufacturers. At present, manufacturers prefer using materials other than lignin- and cellulose-based materials.

Bendable fiberboards made with renewable materials can be found on the market today. Their bendability is achieved by cutting various patterns into the surface or with various sandwich structures, from solid wood and wood particles to polymers (Fathi *et al.* 2013; Gaff *et al.* 2017b). A variety of physical qualities can be used to determine the bendability characteristic, such as the force at the limit of proportionality (F_E), deflection at the limit of proportionality (Y_E), force at the modulus of rupture (F_P), and deflection at the modulus of rupture (Y_P) (Gaff *et al.* 2015; Sikora *et al.* 2017; Svoboda *et al.* 2017).

Unlike the strength, the bendability depends on the thickness of the material. This property is therefore most often expressed as the ratio of the material thickness to the minimum curve radius (*R*min), *i.e.*, the coefficient of bendability (K_{bend}) (Gašparík and Gaff 2015; Gaff *et al.* 2016).

The development of methods, mathematical models, and characteristics used to describe materials is progressing rapidly (Bal 2014). This progress highlights the effort in the development of material engineering to produce materials that meet specific customer requirements, as well as the environmental and economic requirements of production. This development is also associated with the testing of new types of materials that could replace materials that are more expensive and environmentally more valuable, such as wood (Bao *et al.* 2001). There is an increasing need to develop new materials using alternative sources, predominantly lignocellulosic post-harvest residues (Wang and Sun 2002). The main advantages of these raw materials are that they are renewable, recyclable, sustainable, and they can mean a positive difference between the environment of today and that of tomorrow (Guler *et al.* 2006; El-Kassas and Mourad 2013; Marinho *et al.* 2013). The world has a large amount of lignocellulosic residues (approximately 2.4 trillion tons) that is suitable for the production of composite materials and are produced every year after the end of the agricultural season. These residues are either burned or left on the ground, but the fibers of these raw materials have many advantages over some synthetic fibers (Taj *et al.* 2007). These residues include flax, hemp, wheat straw, barley, rapeseed stalks, and more (Bond and Ansell 1998).

Rapeseed (*Brassica napus* L.) is an agricultural crop with a prospective development in the Czech Republic. Although it is not the most widely planted agricultural crop, it is still a relatively important crop for the Czech economy, and the secondary product (stalk) is a suitable material for the production of composite materials. Figure 1 shows the growing tendency for the utilization of sowing areas in hectares for rapeseed in the Czech Republic, according to the Czech Statistical Office. The yield per hectare of rapeseed stalk throughout Europe ranges from 3 tons to 10 tons.

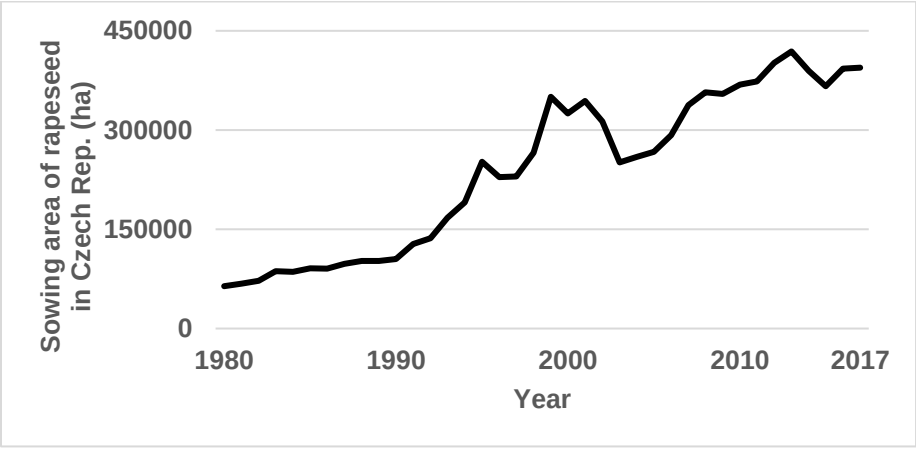

Fig. 1. Increase in the sowing area of rapeseed from 1980 to 2017

The growth of rapeseed, as well as the properties of this material, ranks it among materials with a high potential for use in the manufacture of composite materials (Guntekin *et al.* 2014).

Another equally important factor in the development of the material engineering industry is the correct identification and quantification of material properties (Bal 2014). It has become evident that even today, characteristics that adequately describe important material properties have not been derived and thoroughly examined (Gaff *et al*. 2016, 2017a). A drawback of this industry is that the applied methods are based on approaches introduced in times when the possibilities that modern technology currently offer were non-existent. The implementation of new scientific knowledge (in the form of mathematical models) and the approaches to its identification, on the basis of which important material characteristics can be correctly and quickly identified and quantified, are equally important.

The present study combined the synergistic effect of all of the above-mentioned properties with the implementation of new knowledge in the form of mathematical models in the testing of new materials. New information technology was used to identify important parameters.

EXPERIMENTAL

Materials

Rapeseed chips were used to produce chipboard. The fraction of chips used is shown in Table 1. Two modification methods were chosen, which were hydrothermal modification and modification in an alkaline environment. The hydrothermal modification consisted of boiling the chips in water for 45 min and 100 °C. The boards produced from these chips were marked with H_2O. The modification in an alkaline environment also lasted for 45 min (temperature of solution was 25 °C), and the chips were soaked in a 2% sodium hydroxide solution. The boards produced from these chips were marked with NaOH. To determine the effect of the modifications, boards from raw unmodified rapeseed chips were also produced, and these boards were marked with R. These boards produced by us were 12 mm thick. Two commercial materials were chosen for comparison of the properties of the manufactured boards: a 12-mm thick particle board (PB) (P2 for furniture use) and a 12-mm thick oriented strand board (OSB) (type 3 - load-bearing board for use in humid environments).

Table 1. Representation in the Fractions of the Chopped Rapeseed Straw

Length fraction (mm)	0-0.25	0.25-0.5	0.5-0.8	0.8-1.6	1.6-2	2-3.15	3.15-8
Representation, mass (%)	1.2	2.8	4.8	39.4	20.1	23.1	8.6

DAKOTEX2600, which is a powder glue based on polyester and epoxy resin (Dakota Coatings N. V., Nazareth, Belgium), was used to create the boards. The resination was 10%, and the boards were pressed in a laboratory press (Strozatech, Brno, Czech Republic). The following pressing parameters were chosen: a pressure of 2.3 MPa, press plate temperature of 185 °C, pressing time of 10 min, and press closing speed of 150 s. After 10 min, a temperature of 170 °C was reached in the middle of the boards.

The specimens were conditioned to a standardized equilibrium moisture content under a relative humidity of 65% ± 5% and temperature of 20 °C ± 2 °C in a HCP 108 climate chamber (Memmert, Schwabach, Germany). Thirty samples were used for each set of specimens.

Figure 2 shows the vertical density profiles of the tested materials. While the PB and OSB boards had typical M-shaped vertical density profiles, the boards produced by the authors had opposite density profiles, with the highest density in the middle of the board.

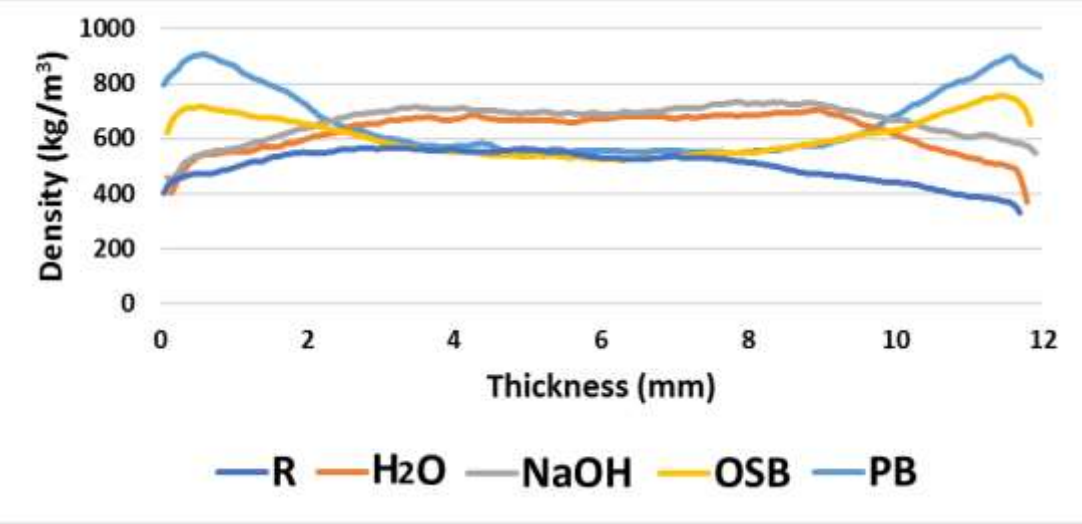

Fig. 2. Density profiles measured for the monitored sets of test samples

Methods

Determination of the characteristics

The bending support span was adjusted to a length of 20 times the thickness. The samples were loaded by three-point bending with a single force in a UTS 50 universal testing machine (TIRA, Schalkau, Germany) according to EN 310 (1993). The loading speed was set to 3 mm/min so that the test duration would not exceed 2 min. The loading forces were measured using the data logger ALMEMO 2690-8 (Ahlborn GmbH, Ilmenau, Germany).

All of the necessary data were obtained from the force-deflection diagrams. To identify the characteristics, a program developed by the authors was used that accurately identified and quantified data that could be obtained from the force-deformation diagram.

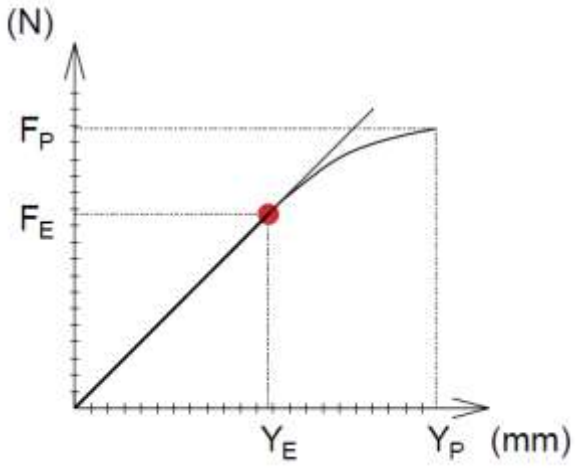

Fig. 3. Force–deflection diagram of bending

Evaluation and calculation

A force-deflection diagram was created using the measured data (Fig. 3), in which a method that the authors developed for accurately identifying boundary points was applied.

Determining the boundary points consisted of determining the exact boundaries between the linear and nonlinear part of the diagram. This is neglected in the standards used today and therefore, subsequent evaluation is quite inaccurate.

In the next part of this study, a bendability evaluation was done using the minimum curve radius and coefficient of bendability. For this analysis, Eqs. 1, 2, 3, and 4 were used, which were deduced by the authors in a previous paper (Gaff *et al.* 2016).

The minimum curve radius (R_{minB}) (Eq. 1) and coefficient of bendability (K_{bendB}) (Eq. 2) were based on the bending geometry, and are as follows:

$$R_{\mathrm{minB}} = \frac{l_0^2}{8\,Y_{\max}} + \frac{Y_{\max}}{2} - \frac{h}{2} \quad (1)$$

$$K_{\mathrm{bendB}} = \frac{h}{R_{\mathrm{minB}}} = \frac{h}{\frac{l_0^2}{8\,Y_{\max}} + \frac{y_{\max}}{2} - \frac{h}{2}} \quad (2)$$

The minimum curve radius (R_{minC}) (Eq. 3) and coefficient of bendability (K_{bendC}) (Eq. 4) are based on the basic bending equations that follow,

$$R_{\mathrm{minC}} = \frac{l_0^2}{12\,Y_{\max}} \quad (3)$$

$$K_{\mathrm{bendC}} = \frac{h}{R_{\mathrm{minC}}} = \frac{h}{\frac{l_0^2}{12\,Y_{\max}}} \quad (4)$$

where R_{minB} is the minimum curve radius based on bending geometry (mm), K_{bendB} is the coefficient of bendability based on bending geometry, R_{minC} is the minimum curve radius based on the basic bending equations (mm), K_{bendC} is the coefficient of bendability based on the basic bending equations, $Y_{\max}$ is the maximum deflection (mm), l_0 is the distance between supporting radius (mm), and h is the thickness of the sample (mm).

The wood density was determined before and after testing according to ISO 13061-2 (2014). The moisture content of the samples before and after testing, along with drying to an oven-dry state were performed according to ISO 13061-1 (2014). Drying to an oven-dry state was also performed according to ISO 13061-1 (2014). The bending strength values were converted to those that corresponded to a moisture content of 12%, in accordance with ISO 13061-3 (2014).

The effect of individual factors was evaluated using an analysis of variance (ANOVA), specifically Fisher's F-test, with the STATISTICA 12 software (Statsoft Inc., Tulsa, USA). The results were evaluated using a 95% confidence interval, which represents a significance level of 0.05 ($P < 0.05$). To deepen the acquired knowledge, Duncan's tests were used to compare the tested sets of specimens.

The effect of the density of the tested materials on the monitored characteristics was verified by a correlation analysis, and the degree of dependence between the characteristics was determined based on the coefficient of determination (r^2). To determine

the degree of dependence, the interaction between individual monitored characteristics was evaluated, for which a correlation analysis and Spearman's correlation were used.

RESULTS AND DISCUSSION

Table 2 shows the average values of the monitored characteristics, as well as the corresponding coefficient of variation for the evaluated materials. The table also shows the average density values measured over the entire cross section of the boards and the average density of the surface zones (1 mm from the surface) of the material.

Table 2. Mean Values of the Y_E, Y_P, F_P, F_E, R_{minB}, R_{minC}, K_{bendB}, K_{bendC}, and the Coefficient of Variation for the Evaluated Materials

Material	Glue	Y_E (mm)	Y_P (mm)	F_P (N)	F_E (N)	Average Density for Entire Thickness (kg/m^3)	Average Density for a Thickness of 1 mm (kg/m^3)
R	PSE	2.9 (17.0)	5.4 (17.4)	108 (18.3)	74 (10.2)	582 (10.4)	456.3 (8.2)
H_2O	PSE	3.2 (12.6)	6.6 (16.8)	201 (13.2)	133 (19.4)	621 (5.3)	487.3 (4.5)
NaOH	PSE	2.8 (16.0)	6.6 (15.5)	157 (18.5)	93 (10.9)	655 (11.1)	508.7 (6.8)
PB	UF	2.0 (16.6)	3.9 (7.8)	238 (9.3)	143 (16.6)	669 (3.0)	862.4 (5.2)
OSB	MUF	2.9 (14.3)	5.2 (18.2)	458 (19.6)	309 (15.9)	619 (3.2)	677.9 (6.1)
Material	**Glue**	R_{minB}	R_{minC}	K_{bendB}	K_{bendC}	**Average Density for Entire Thickness (kg/m^3)**	**Average Density for a Thickness of 1 mm (kg/m^3)**
R	PSE	1282 (21.4)	853 (21.5)	0.009 (17.5)	0.014 (17.5)	582 (10.4)	456.3 (8.2)
H_2O	PSE	1063 (22.5)	707 (22.6)	0.011 (16.8)	0.017 (16.8)	621 (5.3)	487.3 (4.5)
NaOH	PSE	1093 (15.5)	726 (15.6)	0.011 (15.6)	0.017 (15.7)	655 (11.1)	508.7 (6.8)
PB	UF	1897 (7.5)	1263 (7.6)	0.006 (7.7)	0.010 (7.7)	669 (3.0)	862.4 (5.2)
OSB	MUF	1487 (29.0)	990 (29.0)	0.009 (28.1)	0.013 (28.2)	619 (3.2)	677.9 (6.1)

Values in parentheses are the coefficients of variation (CV) in %; PSE = hybrid polyester/epoxide adhesive; MUF = melamine-urea-formaldehyde adhesive; UF = urea-formaldehyde adhesive

Based on the level of significance (P), it was apparent that each of the monitored characteristics was significantly affected by the type of material. In all of the monitored cases, the probability that this factor had no effect was 0.00%, which meant that this factor had a statistically significant effect (Tables 3 and 4).

Table 3. Statistical Evaluation of the Factors Influencing the Y_E, Y_P, F_P, and F_E

Y_E (mm)					
Monitored Factor	**Sum of Squares**	**Degree of Freedom**	**Variance**	**Fisher's F - test**	**Significance Level P**
Intercept	1139.804	1	1139.804	4578.769	***
1) Material	22.834	4	5.709	22.932	***
Error	36.095	145	0.249		
The respective model explained roughly 38.7% of the total sum of squares.					
Y_P (mm)					
Monitored Factor	**Sum of Squares**	**Degree of Freedom**	**Variance**	**Fisher's F - test**	**Significance Level P**
Intercept	4623.372	1	4623.372	4255.367	***
1) Material	145.087	4	36.272	33.385	***
Error	157.540	145	1.086		
The respective model explained roughly 47.9% of the total sum of squares.					
F_P (N)					
Monitored Factor	**Sum of Squares**	**Degree of Freedom**	**Variance**	**Fisher's F - test**	**Significance Level P**
Intercept	8088153	1	8088153	1156.170	***
1) Material	2191905	4	547976	78.331	***
Error	1014368	145	6996		
The respective model explained roughly 68.4% of the total sum of squares.					
F_E (N)					
Monitored Factor	**Sum of Squares**	**Degree of Freedom**	**Variance**	**Fisher's F - test**	**Significance Level P**
Intercept	3390107	1	3390107	717.759	***
1) Material	1043529	4	260882	55.234	***
Error	684861	145	4723		
The respective model explained roughly 60.4% of the total sum of squares.					

NS - not significant, *** - significant, where significance was accepted at P < 0.05

Figure 4 shows the values of the Y_E and Y_P. It was clear from the values in the graph that the highest Y_E was measured in the material developed with the hydrothermally modified chips (H_2O). In the other cases (R, NaOH, PB, and OSB), the Y_E values were significantly lower. The highest Y_P was measured in the H_2O and NaOH materials, with no statistically significant difference found between the Y_P values of these two materials. The other monitored specimen sets (R, PB, and OSB) had significantly lower values than the modified specimen sets (H_2O and NaOH). The significantly lowest Y_P values were measured with the PB material.

The above results indicated that the materials developed in this work (R, H_2O, and NaOH) had higher bendability values than the commercially available materials (PB and OSB), which was characterized by measured Y_E and Y_P values. Sikora *et al.* (2017) also dealt with the assessment of the bendability based on the values of the Y_E and Y_P. The Y_E values ranged from 1.7 mm to 25.4 mm depending on the material thickness and wood species.

Table 4. Statistical Evaluation of the Factors Influencing the R_{minB}, R_{minC}, K_{bendB}, and K_{bendC}

R_{minB}					
Monitored Factor	**Sum of Squares**	**Degree of Freedom**	**Variance**	**Fisher's F - test**	**Significance Level P**
Intercept	279314793.519	1.000	279314793.519	3804.955	***
1) Material	14099251.711	4.000	3524812.928	48.017	***
Error	10644185.168	145.000	73408.174		
The respective model explained roughly 100% of the total sum of squares.					
R_{minC}					
Monitored Factor	**Sum of Squares**	**Degree of Freedom**	**Variance**	**Fisher's F - test**	**Significance Level P**
Intercept	123635360.870	1.000	123635360.870	3775.832	***
1) Material	6286086.973	4.000	1571521.743	47.994	***
Error	4747861.022	145.000	32743.869		
The respective model explained roughly 100 % of the total sum of squares.					
K_{bendB}					
Monitored Factor	**Sum of Squares**	**Degree of Freedom**	**Variance**	**Fisher's F - test**	**Significance Level P**
Intercept	0.013	1.000	0.013	4259.588	***
1) Material	0.000	4.000	0.000	37.744	***
Error	0.000	145.000	0.000		
The respective model explained roughly 100% of the total sum of squares.					
K_{bendC}					
Monitored Factor	**Sum of Squares**	**Degree of Freedom**	**Variance**	**Fisher's F - test**	**Significance Level P**
Intercept	0.030	1.000	0.030	4218.593	***
1) Material	0.001	4.000	0.000	37.675	***
Error	0.001	145.000	0.000		
The respective model explained roughly 100% of the total sum of squares.					

NS - not significant, *** - significant, where significance was accepted at $P < 0.05$

Figure 5 shows the F_E and F_P measured for the monitored sets of test specimens. It was clear from the values in the graph that the highest values of the F_E and F_P were measured in the OSB materials. In contrast, the significantly lowest values were measured in the R material developed in this work.

The results also showed that the H_2O material can withstand the same stress as the PB material at the modulus of rupture, as well as the limit of proportionality, which was considered a positive property of this material. The results of Svoboda *et al.* (2017) showed that for aspen wood a force of 600 N is needed to achieve deflection at the limit of proportionality, and a 1100-N force is needed to achieve deflection at the modulus of rupture.

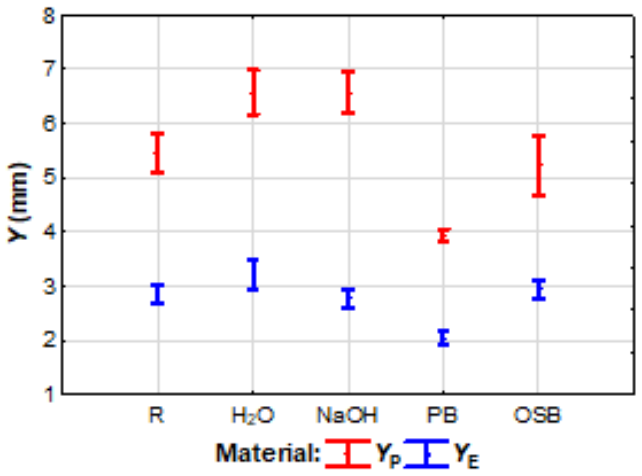

Fig. 4. Effect of the material on the Y_E and Y_P

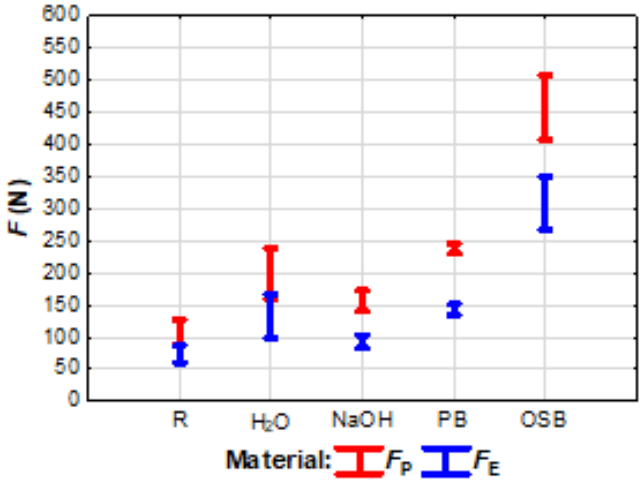

Fig. 5. Effect of the material on the F_E and F_P

Figure 6 shows the values of the minimum curve radius evaluated according to the methodology of Gaff *et al.* (2016). The difference between the R_{minB} and R_{minC} values was approximately 51%, which was consistent with the data reported by Gaff *et al.* (2016). The highest minimum curve radius values were measured in the PB. The lowest minimum curve radius was measured in the H_2O and NaOH samples. The difference between these sets of specimens was statistically insignificant.

The highest K_{bend} was measured in the H_2O and NaOH sets of specimens, and the lowest values were measured in the PB set of test specimens (Fig. 7). The results showed that the materials developed in this work (R, H_2O, and NaOH) had significantly higher bendability values than the commercially available materials (PB and OSB).

In the study (Gaff *et al.* 2016), the K_{bendB} and K_{bendC} of beech and aspen wood were analyzed, and the results of the work showed that there was a 51% difference in the measured values, which coincides with the data measured in this study.

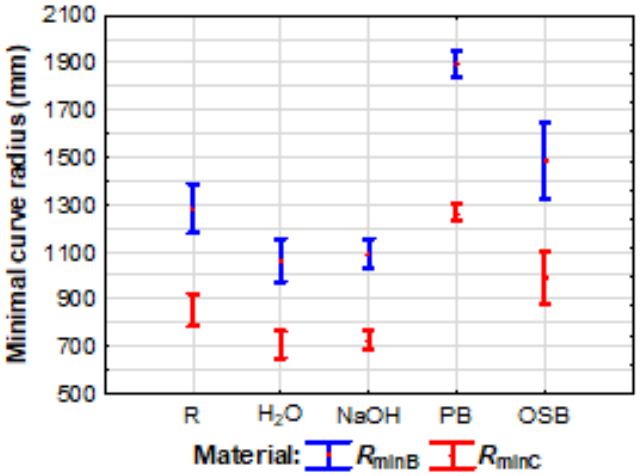

Fig. 6. Effect of the material on the minimum curve radius

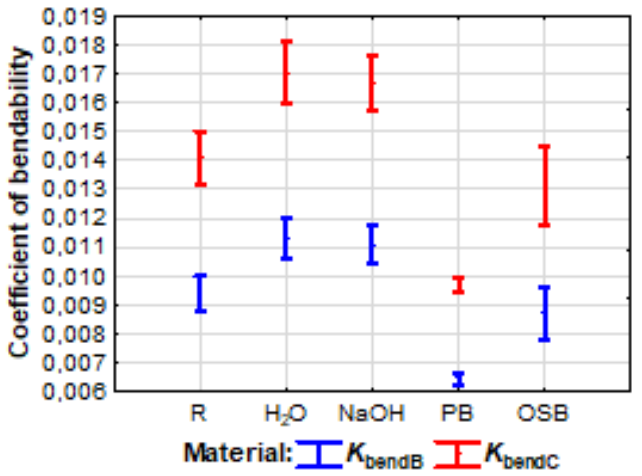

Fig. 7. Effect of the material on the coefficients of bendability

The Duncan's test results show differences between the monitored characteristics of the compared sets of specimens, and are shown in Tables 5 and 6. The data in Table 5 indicated the following findings:

- In the case of the Y_E, there was no statistically significant difference between the R and NaOH specimens (P = 0.467), OSB and NaOH specimens (P = 0.222), and R and OSB specimens (P = 0.566). In the other monitored cases, statistically significant differences in the measured values with a significance level of 0.000 were found.
- In the case of the Y_P, a statistically insignificant difference was confirmed between the H_2O and NaOH specimens (P = 0.990), and R and OSB specimens (P = 0.427). In the other monitored cases, statistically significant differences in the measured values with a significance level of 0.000 were found.
- In the case of the F_P, a statistically insignificant difference was found between the H_2O and PB specimens (P = 0.0083). Between the other sets of test specimens, the difference was statistically very significant with a significance level of 0.000.
- The last monitored characteristic in Table 5 was the F_E. Based on the significance level, it was concluded that there was no significant difference between the values measured for the R and NaOH specimens (P = 0.271), and H_2O and PB specimens (P = 0.589). In the other monitored cases, the differences in the measured values were statistically very significant with a significance level of 0.000.

Table 5. Comparison of the Effect of the Material on the Y_E, Y_P, F_P, and F_E using Duncan's Test

Y_E (mm)						
Material		**(1) 2.8527**	**(2) 3.2083**	**(3) 2.7590**	**(4) 2.0362**	**(5) 2.9266**
1	**R**		0.008	0.467	0.000	0.566
2	**H_2O**	0.008		0.001	0.000	0.029
3	**NaOH**	0.467	0.001		0.000	0.222
4	**PB**	0.000	0.000	0.000		0.000
5	**OSB**	0.566	0.029	0.222	0.000	
Y_P (mm)						
Material		**(1) 5.4463**	**(2) 6.5733**	**(3) 6.5765**	**(4) 3.9303**	**(5) 5.2323**
1	**R**		0.000	0.000	0.000	0.427
2	**H_2O**	0.000		0.990	0.000	0.000
3	**NaOH**	0.000	0.990		0.000	0.000
4	**PB**	0.000	0.000	0.000		0.000
5	**OSB**	0.427	0.000	0.000	0.000	
F_P (N)						
Material		**(1) 107.80**	**(2) 200.67**	**(3) 156.70**	**(4) 238.15**	**(5) 457.72**
1	**R**		0.000	0.024	0.000	0.000
2	**H_2O**	0.000		0.042	0.083	0.000
3	**NaOH**	0.024	0.042		0.000	0.000
4	**PB**	0.000	0.083	0.000		0.000
5	**OSB**	0.000	0.000	0.000	0.000	
F_E (N)						
Material		**(1) 73.540**	**(2) 133.10**	**(3) 93.085**	**(4) 142.70**	**(5) 309.25**
1	**R**		0.001	0.271	0.000	0.000
2	**H_2O**	0.001		0.024	0.589	0.000
3	**NaOH**	0.271	0.024		0.007	0.000
4	**PB**	0.000	0.589	0.007		0.000
5	**OSB**	0.000	0.000	0.000	0.000	

The data in Table 6 indicated the following findings:

- The R_{minB} was significantly affected by the material with a significance level of 0.000. The effect of the material was not confirmed between the H_2O and NaOH materials, which had a significance level of 0.671.
- In the case of the R_{minC}, the same conclusions as for the R_{minB} were reached.
- Very significant differences between the K_{bendB} and K_{bendC} were confirmed by Duncan's test, which indicated a very significant difference between the values measured in the individual materials, with a significance level of 0.000. An insignificant difference was measured between the R and OSB sets of specimens (P = 0.148), and H_2O and NaOH specimens (P = 0.632).

Table 6. Comparison of the Effect of the Material on the R_{minB}, R_{minC}, K_{bendB}, and K_{bendC} using Duncan's Test

R_{minB}						
Material		**(1) 1282.5**	**(2) 1063.1**	**(3) 1092.9**	**(4) 1897.0**	**(5) 1487.4**
1	**R**		0.002	0.007	0.000	0.003
2	**H_2O**	0.002		0.671	0.000	0.000
3	**NaOH**	0.007	0.671		0.000	0.000
4	**PB**	0.000	0.000	0.000		0.000
5	**OSB**	0.003	0.000	0.000	0.000	
R_{minC}						
Material		**(1) 852.18**	**(2) 706.56**	**(3) 726.40**	**(4) 1263.3**	**(5) 989.88**
1	**R**		0.002	0.007	0.000	0.003
2	**H_2O**	0.002		0.671	0.000	0.000
3	**NaOH**	0.007	0.671		0.000	0.000
4	**PB**	0.000	0.000	0.000		0.000
5	**OSB**	0.003	0.000	0.000	0.000	
K_{bendB}						
Material		**(1) .00937**	**(2) .01130**	**(3) .01108**	**(4) .00645**	**(5) .00872**
1	**R**		0.000	0.000	0.000	0.148
2	**H_2O**	0.000		0.632	0.000	0.000
3	**NaOH**	0.000	0.632		0.000	0.000
4	**PB**	0.000	0.000	0.000		0.000
5	**OSB**	0.148	0.000	0.000	0.000	
K_{bendC}						
Material		**(1) .01409**	**(2) .01701**	**(3) .01668**	**(4) .00969**	**(5) .01310**
1	**R**		0.000	0.000	0.000	0.150
2	**H_2O**	0.000		0.631	0.000	0.000
3	**NaOH**	0.000	0.631		0.000	0.000
4	**PB**	0.000	0.000	0.000		0.000
5	**OSB**	0.150	0.000	0.000	0.000	

Correlation Dependence of the Monitored Characteristics and Density

The statistical significance of the monitored factors is shown in Table 7.

Table 7. Analysis of the Dependence of the Individual Factors on the Material Density using Correlation Analyses and Coefficient of Determination of the Y_E, Y_P, F_P, and F_E

Average Density for Entire Thickness					
Material	**Glue**	**r^2 for Y_E (mm)**	**r^2 for Y_P (mm)**	**r^2 for F_P (N)**	**r^2 for F_E (N)**
R	**PSE**	***	***	****	**
H_2O	**PSE**	*	*	***	*
NaOH	**PSE**	**	**	**	**
PB	**UF**	*	*	***	****
OSB	**MUF**	*	*	**	**

Average Density for a Thickness of 1 mm					
Material	**Glue**	**r^2 for Y_E (mm)**	**r^2 for Y_P (mm)**	**r^2 for F_P (N)**	**r^2 for F_E (N)**
R	**PSE**	*	*	*	*
H_2O	**PSE**	*	*	*	*
NaOH	**PSE**	**	**	**	**
PB	**UF**	*	**	**	*
OSB	**MUF**	*	*	*	*

*r^2 < 10% - low tightness; **10% ≤ r^2 < 25% - slight tightness; ***25% ≤ r^2 < 50% - significant tightness; ****50% ≤ r^2 < 80% - high tightness; *****80% ≤ r^2 - very high tightness

Table 8. Analysis of the Dependence of the Individual Factors on the Material Density using Correlation Analyses and Coefficient of Determination of the R_{minB}, R_{minC}, K_{bendB}, and K_{bendC}

Average Density for Entire Thickness					
Material	**Glue**	**r^2 for R_{minB} (mm)**	**r^2 for R_{minC} (mm)**	**r^2 for K_{bendB}**	**r^2 for K_{bendC}**
R	**PSE**	*	***	***	***
H_2O	**PSE**	*	*	*	*
NaOH	**PSE**	*	**	**	**
PB	**UF**	*	*	*	*
OSB	**MUF**	*	*	*	*

Average Density for a Thickness of 1 mm					
Material	**Glue**	**r^2 for R_{minB} (mm)**	**r^2 for R_{minC} (mm)**	**r^2 for K_{bendB}**	**r^2 for K_{bendC}**
R	**PSE**	*	*	*	*
H_2O	**PSE**	*	*	*	*
NaOH	**PSE**	*	**	**	**
PB	**UF**	*	**	**	**
OSB	**MUF**	*	*	*	*

*r^2 < 10% - low tightness; **10% ≤ r^2 < 25% - slight tightness; ***25% ≤ r^2 < 50% - significant tightness; ****50% ≤ r^2 < 80% - high tightness; *****80% ≤ r^2 - very high tightness

The statistical significances of the correlation coefficients among the factors are shown in Table 8.

Correlation Analysis of the Dependence Between the Monitored Characteristics in the Monitored Materials

The results of the correlation analysis showed that there was a high degree of dependence between all of the monitored characteristics in the case of the R material.

The degree of dependence between the monitored characteristics in the H_2O, NaOH, PB, and OSB materials was not as clear as in the case of the R material. There were relationships between characteristics with degrees of dependence where the significance level was less than 50%.

A graphical representation of the correlation dependencies found in individual materials is shown in Figs. 8 to 12. The results presented in Table 9 and Figs. 8 to 12 showed a clear relationship between the increase in the values of one of the monitored characteristics, which affected the increase or decrease in other monitored characteristics.

Table 9. Spearman's Correlation for Each Evaluated Material

R								
Variable	Y_E (mm)	Y_P (mm)	F_E (N)	F_P (N)	R_{minB}	R_{minC}	K_{bendB}	K_{bendC}
Y_E (mm)	1.000	0.428	0.721	0.614	-0.443	-0.443	0.420	0.420
Y_P (mm)	0.428	1.000	0.616	0.685	-0.990	-0.990	0.994	0.994
F_E (N)	0.721	0.616	1.000	0.962	-0.660	-0.660	0.633	0.633
F_P (N)	0.614	0.685	0.962	1.000	-0.728	-0.728	0.705	0.705
R_{minB}	-0.443	-0.990	-0.660	-0.728	1.000	1.000	-0.997	-0.997
R_{minC}	-0.443	-0.990	-0.660	-0.728	1.000	1.000	-0.997	-0.997
K_{bendB}	0.420	0.994	0.633	0.705	-0.997	-0.997	1.000	1.000
K_{bendC}	0.420	0.994	0.633	0.705	-0.997	-0.997	1.000	1.000
H_2O								
Variables	Y_E (mm)	Y_P (mm)	F_E (N)	F_P (N)	R_{minB}	R_{minC}	K_{bendB}	K_{bendC}
Y_E (mm)	1.000	0.654	0.430	0.028	-0.606	-0.606	0.636	0.636
Y_P (mm)	0.654	1.000	0.191	0.214	-0.983	-0.983	0.991	0.991
F_E (N)	0.430	0.191	1.000	0.783	-0.202	-0.202	0.203	0.203
F_P (N)	0.028	0.214	0.783	1.000	-0.271	-0.271	0.240	0.240
R_{minB}	-0.606	-0.983	-0.202	-0.271	1.000	1.000	-0.996	-0.996
R_{minC}	-0.606	-0.983	-0.202	-0.271	1.000	1.000	-0.996	-0.996
K_{bendB}	0.636	0.991	0.203	0.240	-0.996	-0.996	1.000	1.000
K_{bendC}	0.636	0.991	0.203	0.240	-0.996	-0.996	1.000	1.000

NaOH								
Variable	Y_E (mm)	Y_P (mm)	F_E (N)	F_P (N)	R_{minB}	R_{minC}	K_{bendB}	K_{bendC}
Y_E (mm)	1.000	0.073	0.484	0.242	-0.065	-0.065	0.052	0.052
Y_P (mm)	0.073	1.000	0.166	0.423	-0.962	-0.962	0.980	0.980
F_E (N)	0.484	0.166	1.000	0.905	-0.307	-0.307	0.254	0.254
F_P (N)	0.242	0.423	0.905	1.000	-0.566	-0.566	0.519	0.519
R_{minB}	-0.065	-0.962	-0.307	-0.566	1.000	1.000	-0.994	-0.994
R_{minC}	-0.065	-0.962	-0.307	-0.566	1.000	1.000	-0.994	-0.994
K_{bendB}	0.052	0.980	0.254	0.519	-0.994	-0.994	1.000	1.000
K_{bendC}	0.052	0.980	0.254	0.519	-0.994	-0.994	1.000	1.000
PB								
Variable	Y_E (mm)	Y_P (mm)	F_E (N)	F_P (N)	R_{minB}	R_{minC}	K_{bendB}	K_{bendC}
Y_E (mm)	1.000	0.172	0.751	0.233	-0.254	-0.254	0.208	0.208
Y_P (mm)	0.172	1.000	0.138	0.486	-0.979	-0.979	0.995	0.995
F_E (N)	0.751	0.138	1.000	0.635	-0.242	-0.242	0.188	0.188
F_P (N)	0.233	0.486	0.635	1.000	-0.549	-0.549	0.518	0.518
R_{minB}	-0.254	-0.979	-0.242	-0.549	1.000	1.000	-0.990	-0.990
R_{minC}	-0.254	-0.979	-0.242	-0.549	1.000	1.000	-0.990	-0.990
K_{bendB}	0.208	0.995	0.188	0.518	-0.990	-0.990	1.000	1.000
K_{bendC}	0.208	0.995	0.188	0.518	-0.990	-0.990	1.000	1.000
OSB								
Variable	Y_E (mm)	Y_P (mm)	F_E (N)	F_P (N)	R_{minB}	R_{minC}	K_{bendB}	K_{bendC}
Y_E (mm)	1.000	0.317	0.332	0.268	-0.355	-0.355	0.340	0.340
Y_P (mm)	0.317	1.000	-0.299	-0.051	-0.992	-0.992	0.996	0.996
F_E (N)	0.332	-0.299	1.000	0.884	0.258	0.258	-0.273	-0.273
F_P (N)	0.268	-0.051	0.884	1.000	0.008	0.008	-0.022	-0.022
R_{minB}	-0.355	-0.992	0.258	0.008	1.000	1.000	-0.997	-0.997
R_{minC}	-0.355	-0.992	0.258	0.008	1.000	1.000	-0.997	-0.997
K_{bendB}	0.340	0.996	-0.273	-0.022	-0.997	-0.997	1.000	1.000
K_{bendC}	0.340	0.996	-0.273	-0.022	-0.997	-0.997	1.000	1.000

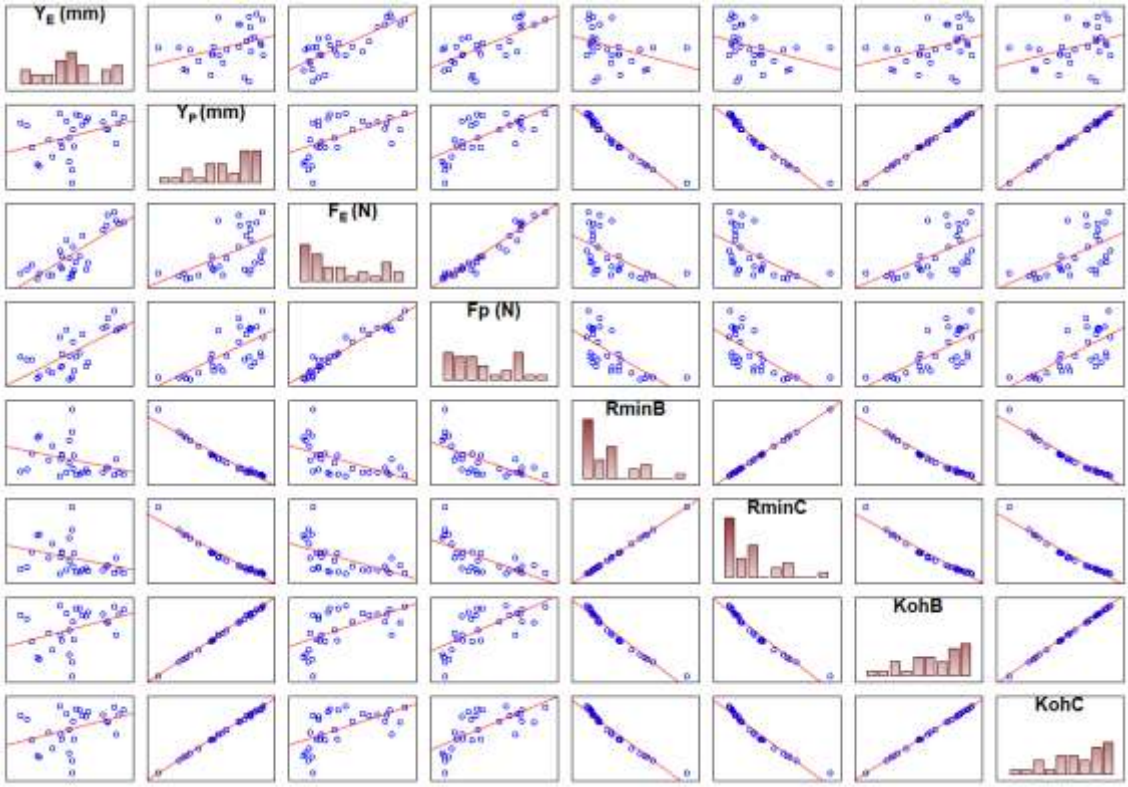

Fig. 8. Correlation matrix of the evaluated characteristics for the R material

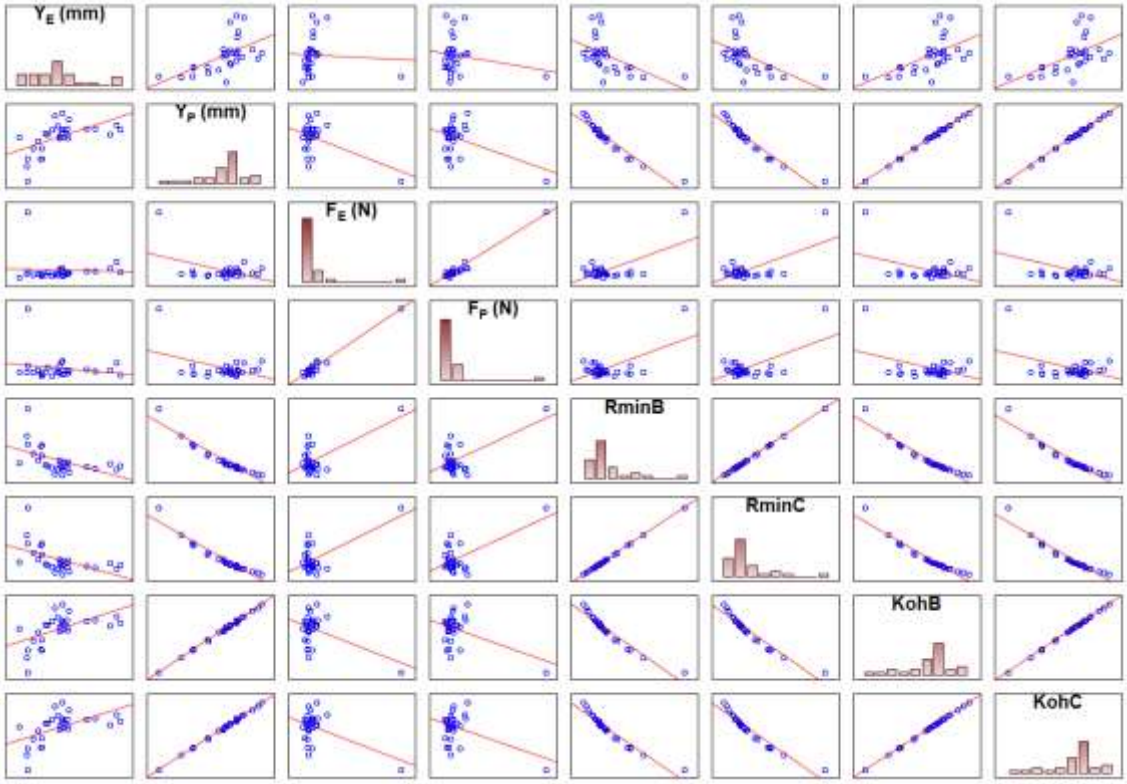

Fig. 9. Correlation matrix of the evaluated characteristics for the H_2O material

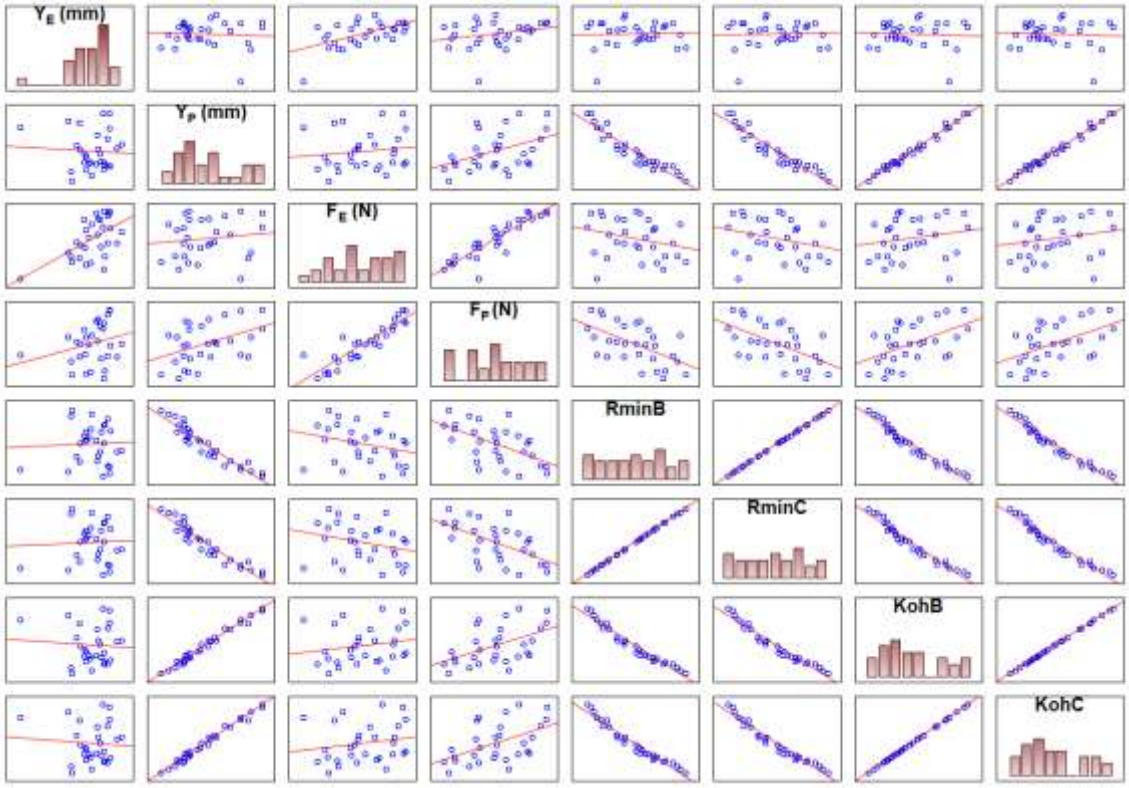

Fig. 10. Correlation matrix of the evaluated characteristics for the NaOH material

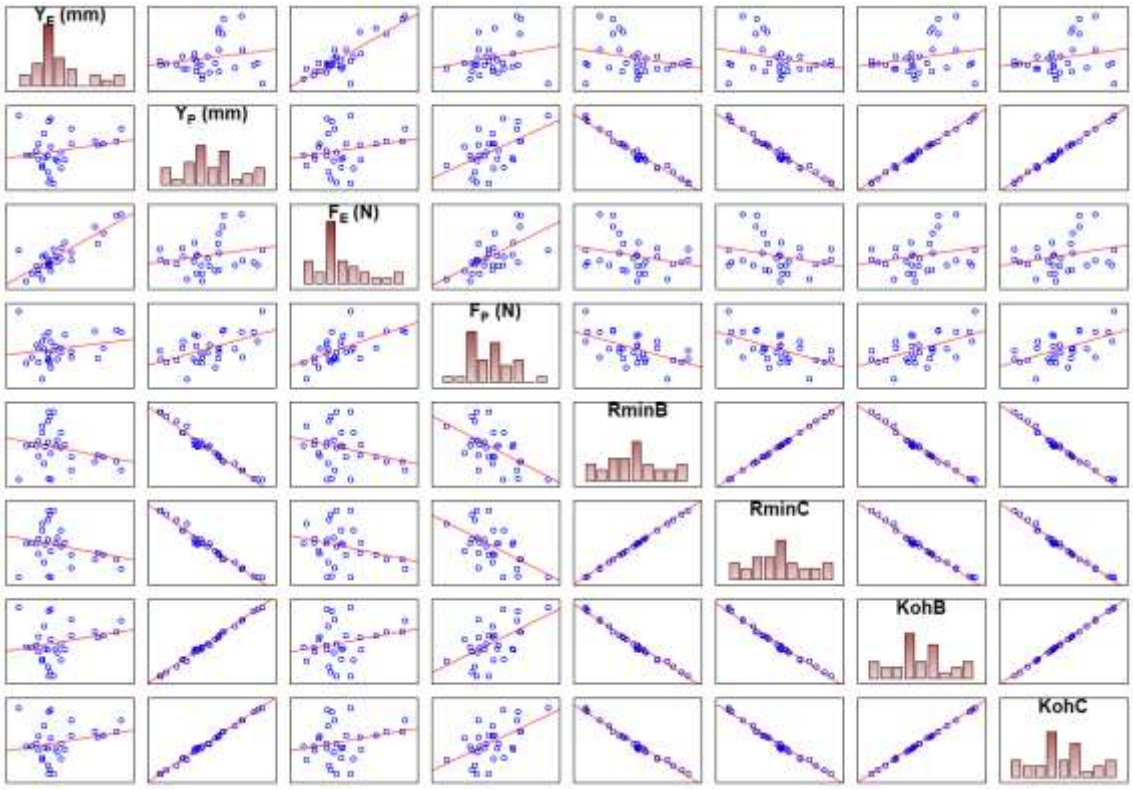

Fig. 11. Correlation matrix of the evaluated characteristics for the PB material

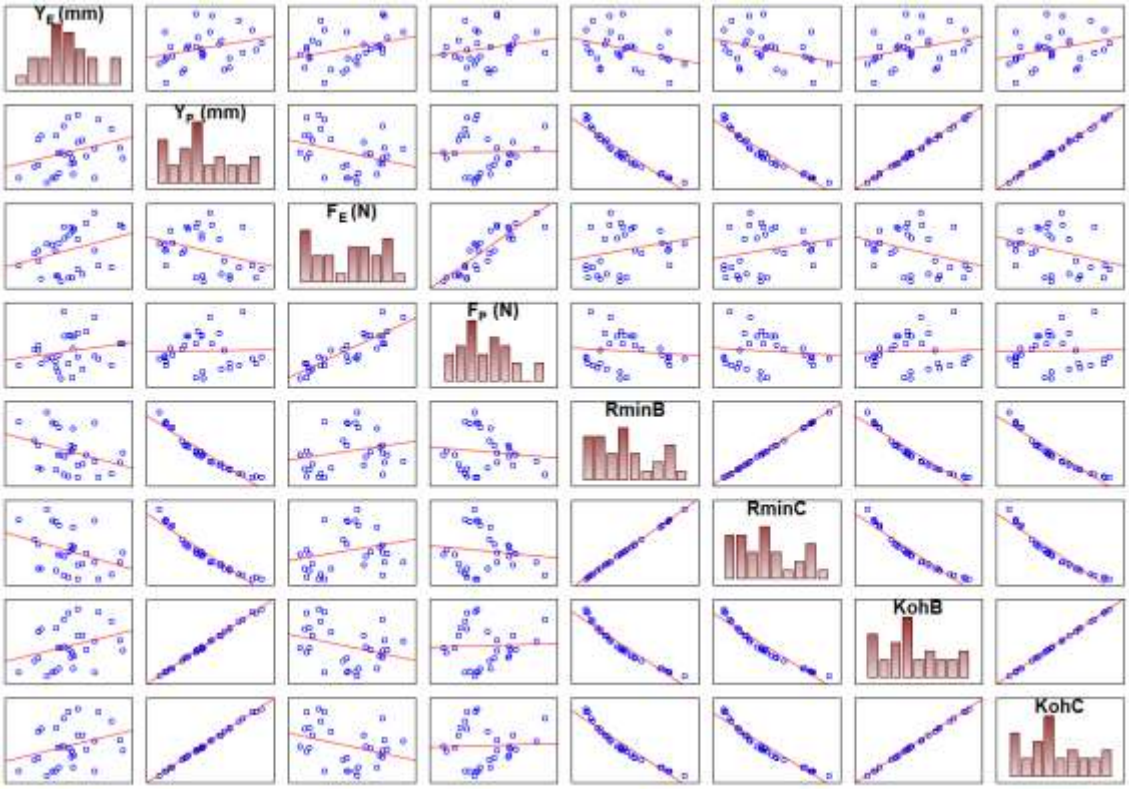

Fig. 12. Correlation matrix of the evaluated characteristics for the OSB material

CONCLUSIONS

1. This article described the bendability of composite materials using completely new software and mathematical models.
2. The results provided comprehensive information about the properties of new composite materials produced from rapeseed residues, as well as commercially available materials with properties that have been unknown until now (PB and OSB).
3. The results indicated that rapeseed can fully replace precious raw materials (wood), and thus increase the protection of the natural environment and ensure the better utilization of waste, which undoubtedly has an impact on the economic indicators of society.
4. The results showed that the materials developed by the authors had significantly higher bendability values (H_2O and NaOH) than the commercially produced materials (PB and OSB). These materials can replace commercially produced materials, which are used for the production of bent furniture components. The properties of the rapeseed boards can be technologically modified.
5. The research showed that biocomposites produced with renewable and available raw materials have excellent bending characteristics, and it is possible to use these materials for special applications.

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