Mat Compression Measurements During Low-Density Particleboard Manufacturing

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This study regards the effect of technological aspects on mat compression during the manufacturing of low-density particleboards made of two low density species - *i.e.* poplar and pine. Using these materials, three-layer low-density particleboards (500 kg/m^3) were prepared. Three series were manufactured: (1) neat pine, (2) poplar-pine (face layer and core layer, respectively) and (3) neat poplar boards. Measurements of real-time variations in mat core temperature, pressure, and mat thickness allowed for the analysis of the mat compaction. Selected mechanical properties (modulus of rupture, modulus of elasticity, and internal bonding) of the manufactured particleboards were determined. Raw material of lower density used for particleboard manufacturing required either prolonged pressing time or more intense heat transfer into the mat core. The highest strength values were obtained for the poplar-pine particleboards.

Keywords: Particleboard; Low density; Poplar; Pine; Pressing process; Raw material

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INTRODUCTION

The development of the furniture industry is connected with the implementation of innovative solutions in particleboard technology. There is a deficiency of wood results in the intensified research on alternative raw material resources (Papadopoulos *et al.* 2002; Abdul Khalil *et al.* 2010; Nicewicz *et al*. 2012; Gatani *et al.* 2013; Varanda *et al.* 2013). Waste wood, annual crops, and fast-growing species have recently become valuable raw materials for particleboard manufacturers (Strauss *et al.* 2004; West 2006; Carle and Holmgren 2009). To adopt alternative low-density materials for existing technology, the proper analysis and characterization of the variations in process parameters as well as the phenomena taking place in the mat are required. One of the most important parameters is mat compression ratio.

Switching to non-classical raw materials allows maintenance of the growth and competitiveness of the wood-based panel industry. The use of annual crops and low-density fast-growing species in manufacturing of novel types of composites for the furniture industry has increased in the last decade. The increase comes from the market needs, and introduction of new materials to the market is most welcomed (Sellers *et al.* 1993; Wang and Sun 2002; Xu *et al.* 2004; Meinlschmidt *et al.* 2008). The main advantage of new types of panels over the old ones is a lowered density. It is known from the literature that the density of woody material affects the compression ratio of a mat, which subsequently determines the properties of the final product (Buschbeck *et al.* 1961a,b; Moslemi 1974; Grigoriu 1981; Clad 1982; Xu *et al.* 2004; Haelvoet and Medved 2009). The reduced panel density renders a decrease in mechanical strength.

Thus, pressing the mats formed from low-density chips requires altered process parameters (*i.e.*, pressure and temperature regimes) (Moslemi 1974). An effectively modified pressing scheme (temperature, pressure, and time) should provide a proper cross-sectional density profile and expected mechanical performance, while overall panel density is decreased. It is recognized that reduced pressure imposes a prolonged pressing time and yields more uniform density profile. On the other hand, an increased pressure results in a higher compression ratio for face layers and a lower one for the core layers of a panel (Keylwerth 1958; Plath 1971; Wong *et al.* 1999; Dunky 2001).

Phenomena occurring during pressing of particleboards play a crucial role in their manufacturing, as the applied regimes determine the final properties of the product. Thus, better recognition and description of variables makes easier optimization of processes possible and, as a result, minimizes production costs, so that implementation of new technologies or products becomes easier.

It is commonly agreed that pressing is necessary for the compression of a mat to the target thickness and for the proper development of adhesive interactions between wood particles. The compression is primarily affected by (1) the pressure and amount of binder, which determine the contact area between chips; and (2) the temperature governing the curing of the binder and development of bondlines (Moslemi 1974). Other factors affecting mat compression process include time, press closing rate, target density of the product, type and amount of binder, as well as characteristics of the material subjected to bonding: chip dimensions, density, and moisture content.

Although there are numerous reports regarding the effect of the factors mentioned above on the compression process during manufacturing of wood-based composites (Kelly 1977; Steffen *et al.* 1999; Miyamoto *et al.* 2002; Dai *et al.* 2004; Nemli *et al.* 2007; Cai *et al.* 2009), none of them considers the compression of low-density particleboards. Therefore, in this paper, some aspects of low-density mat compression are discussed. Particleboards made of softwood, hardwood, and their mixtures are compared.

EXPERIMENTAL

A total of 15 three-layer particleboards of density 500 kg/m^3 with dimensions of 320 x 320 x 18 mm^3 were made. 5 panels were prepared in each series: (1) industrial poplar chips, (2) industrial pine chips, and (3) both poplar (face layers) and pine (core layer) chips. The moisture contents were as follows: poplar 3.5% (face layer) and 2.9% (core layer); pine 5.0% (face layer) and 4.5% (core layer). Wood densities were 450 and 520 kg/m^3, respectively, for poplar and pine.

A commercial urea-formaldehyde (UF) resin was used as a binder, hardened with 10% aqueous ammonium sulfate solution (3% for face layers, 4% for core layer (based on resin solids). Glue rates were as follows: face layer 12% and core layer 8%. A paraffin emulsion was used as a hydrophobic agent (1% based on dry wood).

All the mats were cold pre-pressed at 0.5 MPa pressure for 30 s. The difference in bulk density of pine and poplar chips, resulted in variations in the final thickness of the mats subjected to hot-pressing. In order to achieve comparable board density, the weight of the respective mats was constant. Hot pressing parameters were adopted from industrial conditions and from the literature (Moslemi 1974). Maximum unit pressure upon board pressing was set at 2.5 MPa, however the true momentary pressure was computer-controlled as follows: (1) increased until target thickness is achieved and then

(2) reduced. Other hot pressing parameters were as follows: platen temperature of 180 °C, pressing factor 18 s/mm, press closing rate 2 mm/s, time 324 s. The mat compression process was performed using a computer-controlled press.

Variables (mat core temperature with accuracy ± 0.01 °C, pressure with accuracy ± 0.01 MPa, and mat thickness with accuracy ± 0.01 mm) were monitored in real time throughout the pressing process for each batch, using the computer controller. Temperature measurement inside the mat was carried out using a Fe-CuNi thermocouple, fixed in the mat core during its formation.

Prior to testing, the boards were conditioned at 20 ± 2 °C and 65 ± 5% RH for seven days. The modulus of rupture (MOR) and modulus of elasticity (MOE) were tested according to European standard EN 310 (1993), and the internal bond strength (IB) was determined according to European standard EN 319 (1993). All mechanical tests were conducted using an electromechanical testing machine Instron model 3369 (Instron Corp., Norwood, MA). Ten specimens were tested in each series. Density profiles were measured on an X-ray density analyzer GreCon Da-X (Fagus-Grecon Greten GmbH & Co. KG, Alfeld-Hannover, Germany) at a scanning speed of 0.5 mm/s.

Statistical analysis was performed using STATISTICA version-12 software (StatSoft, Inc., Tulsa, OK). Statistical analysis for all stages of the research was performed at a significance level of 0.05.

RESULTS AND DISCUSSION

As Fig. 1 indicates, the compression processes can be differentiated for the respective series of boards. The temperature (Fig. 1a), mat thickness curves (Fig. 1b), and pressure (Fig. 1c) were varied. Assuming a constant press-closing rate (2 mm/s), the main factor determining the locus and shape of the pressure curve was the mat thickness, which was affected by the properties of the material. The obtained initial uncompressed mat thickness was as follows: 80 mm for poplar (450 kg/m^3), 60 mm for pine (520 kg/m^3), and 70 mm for the mixed poplar-pine mats. The different initial mat thickness comes from the variable chip bulk density. We assumed manufacturing boards of same density, so in case of a "heavier" material, its amount was smaller.

The shortest time (21 s) and the lowest pressure (1.38 MPa) necessary for the mat to be compressed to the target thickness (18 mm) were observed for pine, while for poplar mat, the respective values were 38 s and 1.57 MPa, while midway values were recorded for the mixed poplar-pine mats, *i.e.*, 26 s and 1.61 MPa, respectively. Despite the differences in mat compressing (Fig. 1b), their pressure curves were similar (Fig. 1c). It should be noted that at the moment the mat reached the target thickness (18 mm), the initial temperature was still observed in the core layer. The temperature in the core began to increase gradually but not before the 40th second of the pressing process. Unlike the poplar and poplar-pine boards, the temperature increased above 80 °C in the pine mat core and then slowed, which might be caused by the evaporation of the volatile organic compounds present in pine wood (McDonald *et al.* 1999a,b).

As Fig. 1a indicates, the target temperature of 100 °C in the mat core was achieved after 200, 135, and 143 s, respectively, for poplar, pine, and poplar-pine boards. It was also found that when the mat core temperature reached 100 °C, at which partial plasticizing of the chips occurred, the pressure required for mat thickness control remained at a low level of approximately 1 MPa and was comparable regardless of the series.

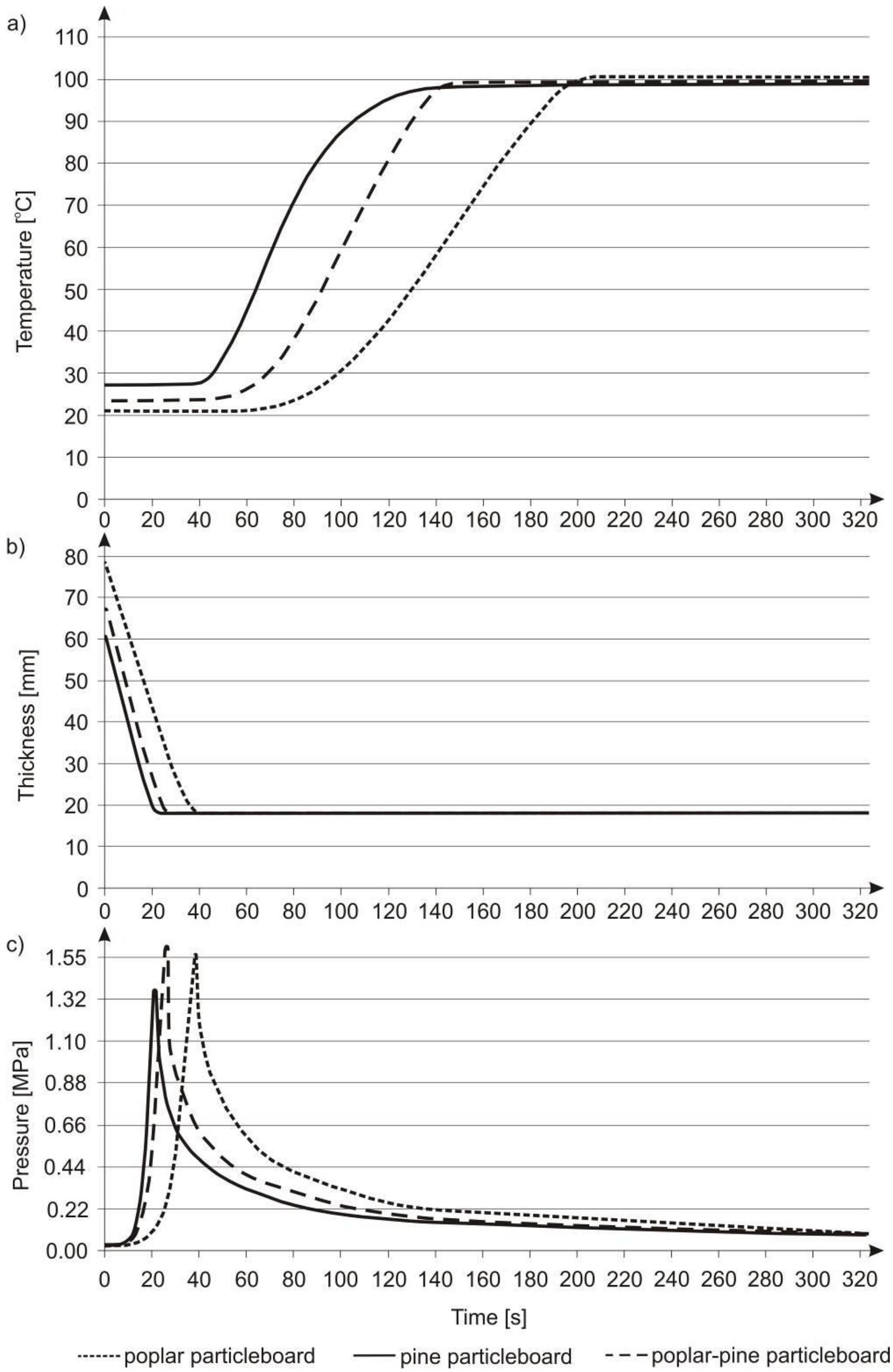
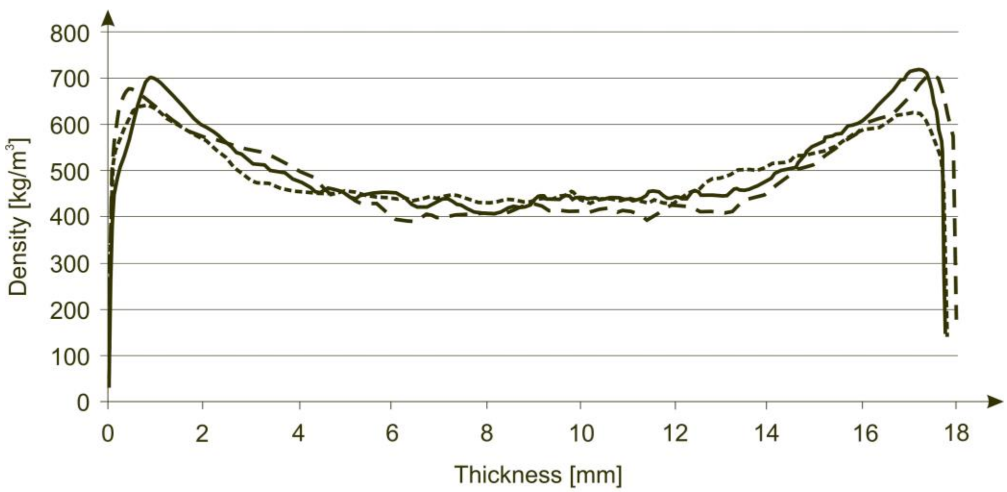


Fig. 1. Pressing parameters recorded during compression of particleboards (500 kg/m^3) - (a) temperature, (b) thickness, (c) pressure

The highest heat transfer rate observed for pine mats was associated with a moisture content higher than that of the poplar material (5.0% face layer and 4.5% core layer *vs*. 3.5% face layer and 2.9% core layer), lower compression of the core layer (minimum density 402 kg/m^3, Fig. 2), and subsequent easier steam penetration, which is the main heat carrier from face layer to core layer upon overheating (Sokolovs`kyi and Petriv 2007).

In addition, the heat transfer coefficient for pine wood was higher than that for poplar (pine, 0.14 W/mK; poplar, 0.10 W/mK (Niemz 1993)), which explains the higher heat transfer rates. Moreover, the lower heat transfer rates observed for poplar might come from higher compression of the mats (minimum density 431 kg/m^3, Fig. 2), which is a hindrance to steam penetration. Because of the lower heat transfer rate, the plasticizing of the chips took more time. Slower heating resulted in more uniform compression of the boards (Fig. 2). In effect, a higher pressure was necessary to hold the target thickness of the mat for the poplar boards.

For the poplar-pine boards, middling heating times and moderate steam penetration were observed. This may have been a result of the mediocre compression of the core layer (minimum density 386 kg/m^3) and its fairly porous structure.



	Density [kg/m³] Maximum (Left / Right)	Minimum (Core)
------- poplar particleboard	642 / 627	431
—— pine particleboard	703 / 720	402
– – – poplar-pine particleboard	677 / 705	386

Fig. 2. Density profiles of the tested panels

Considering the mechanical properties of the manufactured panels (Fig. 3), it can be summarized by stating that the requirements for a P1 panel type (EN 312 (2010) - tab.1) were met to some extent by the respective panel series. Thus, the modulus of rupture (MOR) requirement was met by the poplar panels, pine panels, and mixed poplar-pine panels at 92%, 60%, and 71%, respectively, while the internal bond strength (IB) requirement was met respectively at 60%, 73%, and 100%.

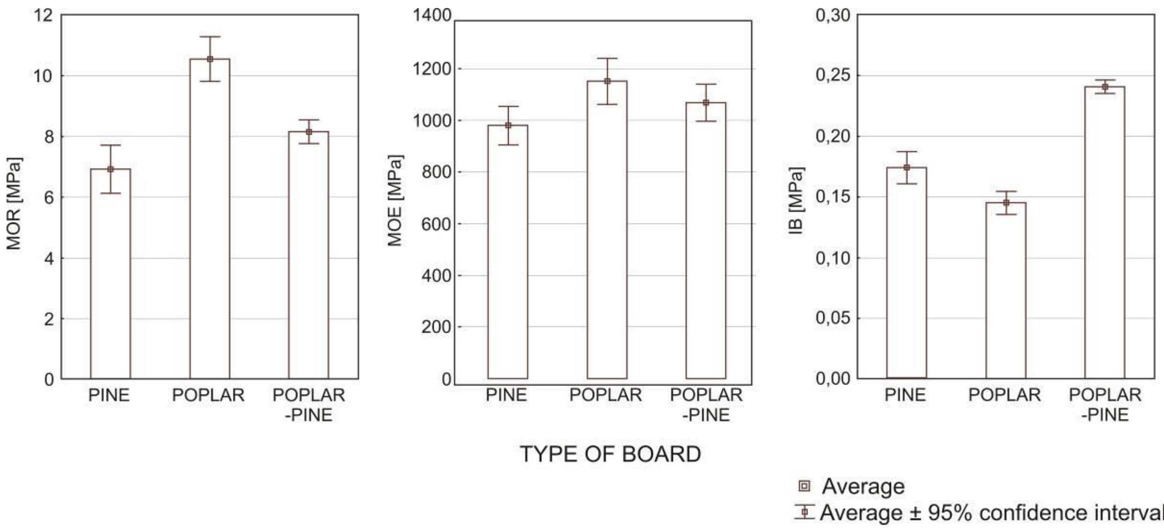


Fig. 3. Differences in mechanical properties (modulus of rapture (MOR), modulus of elasticity (MOE), and internal bond strength (IB)) of the tested panels

Table 1. General Purpose Boards for Use under Dry Conditions (Type P1) - Requirements for Specified Mechanical Properties (MOE for P1 boards is not defined by the standard)

Property	Test method	Unit	Requirement							
			Thickness range (mm, nominal)							
			< 3	3 to 6	> 6 to 13	> 13 to 20	> 20 to 25	> 25 to 32	> 32 to 40	> 40
Bending strength (MOR)	EN 310	N/mm^2	11.5	11.5	10.5	10	10	8.5	7	5.5
Internal bond (IB)	EN 319	N/mm^2	0.31	0.31	0.28	0.24	0.20	0.17	0.14	0.14
NOTE: The values are characterised by moisture content in the material corresponding to a relative humidity of 65 % and a temperature of 20 °C.										

It should be also noted that all the variants of panels in terms of MOR and MOE met the requirements for lightweight particleboard LP1 (CEN/TS 16368 (2014)), while the IB requirement was met by poplar-pine particleboard.

It is commonly agreed that the MOR of a panel is strongly correlated with the density of the face layers and mat compression, which are in turn determined by the chip geometry and their density. Lower density leads to a higher compression ratio of a mat and higher contact surface between chips is developed, so that the total bondline surface is larger (Grigoriu 1981; Xu *et al.* 2004). The data indicated that the highest MOR and MOE values were obtained for the panels containing poplar face layers, while the highest IB were observed for the mixed poplar-pine and neat pine panels. Higher MOR and MOE for poplar series resulted primarily from the higher chip compaction and lower porosity in a layer, while the densities of the face layers remained similar to each other (Fig. 2, Fig. 4). Figure 4 indicates that the structure of the poplar boards was more compact, which resulted from lower bulk density of poplar raw material and its easier compaction. Thus, internal empty spaces volume is minimized and no clear boundary between face and core layers can be observed. The porosity of core of the pine and mixed boards was higher than that of the neat poplar boards, though the minimum densities are comparable (Fig. 2). The phenomenon results directly from the difference in wood density. The density of wood significantly affects the mat compaction ratio by the reduction of free volume between chips (Medved and Resnik 2006). The final properties of a panel can be even more influenced when different wood species are used in the face and core layers. Xu and Suchsland (1999) observed that MOR, MOE, and IB were higher for panels made of one species when compared with mixed ones. The results obtained in the present work for IB are not consistent with the abovementioned findings.

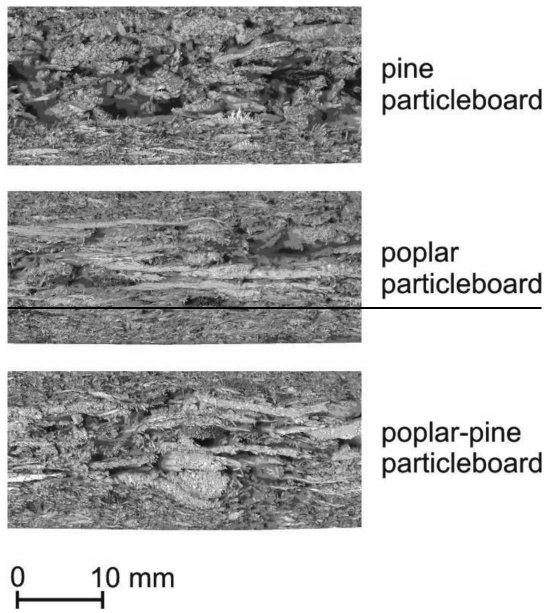


Fig. 4. Internal structure of the tested panels

It is likely that the increase in IB for the mixed poplar-pine boards, when compared with the other two series, comes from the fact that the bulk density of pine chips was higher than that of poplar. Thus, assuming a constant glue rate, the amount of the adhesive loaded on the core layer was higher for the mixed boards than that for the neat poplar ones. On the other hand, the poplar face layers of the mixed boards were compacted to a higher extent because of their lower bulk density, which resulted in a higher pressure transferred onto the pine core layer. A combination of these two factors may have led to the increase in IB observed for the mixed poplar-pine boards.

It is worth noting that the differences between mechanical parameters (MOR, MOE, and IB) found for the studied series were statistically significant at 95% confidence interval. The effect of density variation on the analyzed parameters is shown in Fig. 5.

The alternations in density affect the strength parameters of the boards (Xu and Suchland 1998). The correlation was true for the investigated poplar and pine boards within the analyzed density range (450 to 550 kg/m^3). The strongest correlations were found for the poplar panels, *i.e.*, r^2 for MOR and MOE was, respectively, 0.4579 and 0.9362. The values achieved for the pine boards were 0.6412 and 0.2581, respectively, for MOR and MOE.

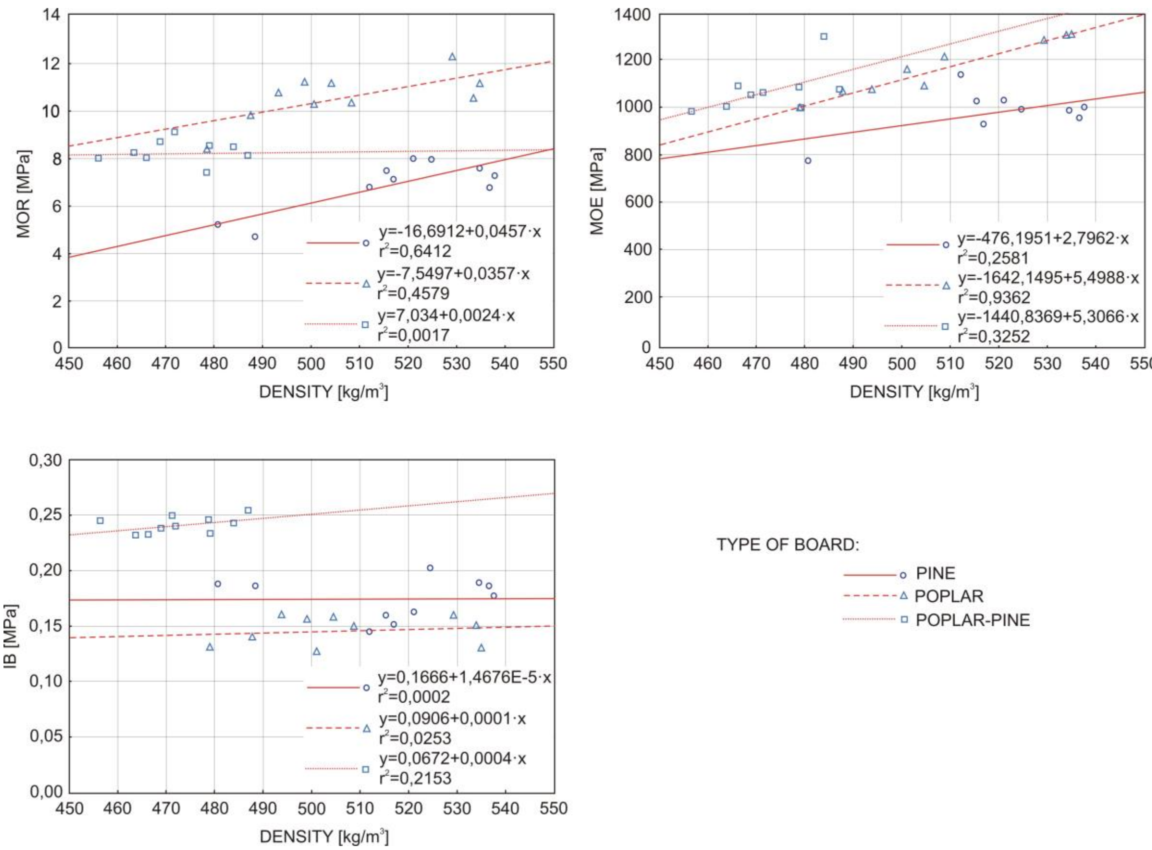


Fig. 5. The effect of density variation on the analyzed parameters (modulus of rapture (MOR), modulus of elasticity (MOE), and internal bond strength (IB)) of the tested panels (*y* - variable correlation equation, r^2 – coefficient of determination)

No statistically significant correlations between density and MOR/MOE were found for the mixed poplar-pine boards (450 to 490 kg/m^3). The r^2 for IB ranged from 0.002 to 0.2153, which indicated no statistical significance. It was observed that both uneven density in the core layer and increased porosity resulted in a decrease in correlation between the density and mechanical performance of a board (MOR and MOE). Analysis of the data for the mixed poplar-pine boards showed lower correlation, which probably resulted from the variable rate of poplar and pine chips in the core layer. The compaction of the face layers that determine MOR and MOE was not altered.

CONCLUSIONS

1. Compression processes during manufacturing of low-density particleboards depend on the species used, their heat transfer coefficients, and their moisture content.
2. These factors also affect heating times, so that pressing regimes must be carefully considered and empirically verified.
3. Raw material with lower density used for particleboard manufacturing requires either prolonged pressing times or higher heat transfer into the mat core.

4. In terms of mechanical properties, poplar-pine particleboards exhibited the best performance.

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