Annals of Warsaw University of Life Sciences - SGGW
Forestry and Wood Technology № 116, 2021: 96-110
(Ann. WULS - SGGW, For. and Wood Technol. 116, 2021: 96-110)

Compression strength-focused properties of wood composites induced by density

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Abstract: *Compression strength-focused properties of wood composites induced by density.* The aim of this study was to analyse the contractual compression strength and modulus of elasticity under compression of ten commercially available wood composites of various thickness, density, structure and surface finish. Density and density profiles have also been performed. The tests showed that there is no significant dependence of the compression strength and MOEC on the density of composites.

Keywords: particleboard, fibreboard, plywood, mechanical properties, compression, MOE

INTRODUCTION

Recently, particleboards became more popular than solid wood in a common usage. The wood industry values most of all their lower price and unified mechanical properties. Depending on which performances are required, the particleboards can be produced in a way to fulfill them. Nowadays, it is possible to produce such particleboards from various materials and with numerous technological methods. It all provides specific properties. Many researches on material's influence have already been done.

ATTA-OBENG *et al.* (2012) tested the effect of microcrystalline cellulose, species and particle size on mechanical and physical properties of a particleboard. The species used in this study were: sweetgum (*Liquidambar styraciflua*) and southern pine (*Pinus spp*.). Wood-based materials were made at a small and large particle size and at 0 and 10% microcrystalline cellulose loading. The study showed, that increasing particle size has a positive impact on mechanical properties. Conversely, mechanical properties and springback decreased with adding microcrystalline cellulose. Similar research of the influence of particle size on the properties of particleboard have been conducted by SACKEY *et al.* (2008). The produced boards were single- and 3-layer, at two density levels from four types of mixes. Board mean, density, modulus of rupture, modulus of elasticity, internal bond (IB) strength, as well edge screw withdrawal resistance (SWR) were measured. Studies showed that single-layer boards indicated only a slight increase in bond strength and edge-SWR by replacing 40% of the coarse particles with medium and fine ones, and decreased by further increase in fines content. The effect of fines in the particle mix of 3-layer boards worked in those compressed to low density. What is more, boards made using cores containing customized mix of particles showed up to 40% higher IB and 18% better edge-SWR, than boards produced with industrial furnishings. Flexural properties of the 3-layer boards were unaffected by core fines content.

MO *et al.* (2001) investigated the compression and tensile strength of low-density straw-protein particleboard. Surface treatment of straw with bleach gave better results than those with hydroperoxide – alone and combined with sodium hydroxide treatment. The best mechanical properties showed particleboards with sodium hydroxide-modified soy. The optimal initial straw moisture content providing good bonding was about 30-40%.

MAKU and HAMADA (1955) carried out studies on the chipboard for the determination of the relation between moisture content, specific gravity, shearing strength, modulus of elasticity in compression and tension, tensile and compressive strength. Their researches included two basic types of wood particles. The results showed that with the increase of density, the increase of strength and MOE is observed as well. They also found that the produced panels' tensile strength is comparatively smaller than the compressive strength.

RIEGLER *et al.* (2012) made studies on the influence of hardwood on the vertical density profile and fracture energy of particleboards. These wood-based materials made of poplar, willow and black locust were investigated for their fracture mechanical properties. As a reference, the authors used virgin spruce wood (usually used as a raw material in the core layer of particleboards), as well as recycled wood chips. The results showed that the poplar and willow core particleboards performed higher fracture energy values. The explanation for this could be a better consolidation under pressing showed by lower density hardwood particles. The penetration of resin into particles is higher than by higher-density wood and the contact between the wood surfaces is closer. Regarding wood raw material and particleboard relation , VITAL *et al.* (1974) made a research on how exotic hardwood species and board density affect properties of particleboard. The authors used four exotic hardwood species, kiri (*Paulownia tomentosa*), Virola (*Virola spp.*), limba (*Terminalia superba*), and afrormosia (*Pericopsis elata*), to make 3-layer particleboards. The results of the study showed that MOE and MOR increased linearly with density (of wood and of a particleboard as well). Boards with the same density showed higher MOR and MOE when treated with high compression, than those with the lower. Moreover, properties of single-species particleboards and mixed-species boards were very similar in MOE and MOR – as measured for the weighted mean of the results noted for single species. As regards IB depending on density, regression lines mostly were not parallel. IB is influenced by geometry of particles, high IB strengths are related to high content of small particles in a board.

CHIANG *et al.* (2016) researched effects of density of sago/urea formaldehyde particleboard towards its thermal stability, mechanical and physical properties. Several trail of mixing process was conducted. The study showed that majorly important factors that affect the density profile of a particleboard are: particle configuration, pressing time, temperature of the hot press, moisture distribution, reactivity of the resin and compressive strength of the component of the sago particles. Increasing temperature of the hot-press caused a bigger mass change of the board. Increasing density allowed it to decrease that occurrence. The internal bond of produced panels has raised significantly (from about 0.22 to 0.55 N/mm^2) when the panels' density raised from 500 to 600 kg/m^3, and the IB changes have been not so significant when the density was increased to 800 kg/m^3. The significance of the density profile has been confirmed by SUO and BOWYER (1994) in simulation modelling of particleboard density profiles. The factors affecting wood compressibility, temperature and moisture could be determined at any moment of pressing. The study allowed to model density profile basing on the compressibility and the strain of each board thickness' layer due to pressing. The authors claim that once the density profile is done, it can be used as a major factor in predicting and describing particleboard's properties. Summing up, density can be modelled and is one of the most important features of a wood-based material.

KAWAI *et al.* (1986) carried out the research on physical properties of low-density particleboard. The main factors affecting the strength were pressure and time of pressing. Three density-levels were adopted: 300; 400 and 500 kg/m^3. Raw materials used in the study was Seraya (*Shorea spp.*) – end logs and core bolds with density of 400 kg/m^3. The results showed, that MOE and MOR increase proportionally to density. Also the thickness of a particleboard proportionally increases its properties. Veneer-overlaid wood-based materials showed improved MOE and MOR, competing with non-overlaid ones. Other factors did not seem to influence the mechanical properties that much. According to board density, KAI *et al.* (2004) made a research on the influence of board density, mat construction and chip type on performance of particleboard made from eastern redcedar. The authors adopted two types of chips (whole tree and pure wood), two types of mat constructions (single- and three-layer), and four density levels – 400; 500; 650 and 750 kg/m^3. Results showed, that biggest impact on mechanical properties had density and mat construction. Chip type did not affect properties significantly. 3-layer particleboards gave better results than single-layer ones, including MOR, MOE, IB and surface hardness.

LENG *et al.* (2017) studied effects of density, cellulose nanofibrils (CNF) addition ratio, pressing method and particle size on the bending properties of wet-formed particleboard. The materials used in the test were particles consisting of an 80 : 20 ratio of softwood : hardwood. Two pressing methods were evaluated: CT (constant thickness) and CP (constant pressure). Results showed that density had the biggest impact on MOE, while the CNF influenced MOR the most. As regards panels with the low density (< 640 kg/m^3), the MOR and MOE did not change much after manipulating particle size and pressing method. For wood-based materials of medium density (640 – 800 kg/m^3), the best properties were reached by using larger particles, higher CNF ratio and CT pressing method. Panels pressed with higher CP of 0.55 MPa showed better properties for higher densities. A higher hot-press pressure generated higher density which caused better interfibre bonding. CT pressing method – comparing with CP method - provided more acceptable (higher) bending performance, especially combined with higher CNF ratios. Summing up, increasing density and CNF volume at the same time, would improve the performance of mechanical properties of a particleboard.

MIYAMOTO *et al.* (2002) made a research on effects of press closing time on mat consolidation behavior during hot pressing and on linear expansion of 10 mm thick particleboards. The properties were investigated at various press closing times (PCTs). The species used in this study was hinoki (Japanese cypress). Press pressure, temperature in the core layer of the mat and platen distance were measured. The results show that peak density (PD) decreased with increasing PCT, while core density (CD) - increased. The bending properties decreased with increasing PCT. IB strength increased with increasing CD in the PCT range 4-300 s. IB represents here the tensile strength of the core layer. Worth noticing is, that PCT of 900 s resulted in lower IB despite its higher CD. That is because such board did not have enough bonding strength (resin pre-curing has started). MOE, MOR and density tend to decrease with increasing PCTs.

Not only bending was the subject of studies on wood-based panels' mechanical properties. There have been few researches on compression strength and modulus of elasticity when compressing done.

FERRO *et al*. (2013) carried out study on verification of test conditions to determine the modulus of compression elasticity of wood. The investigated species were *Pinus elliottii* and *Corymbia citriodora*. The study showed not significant influence of dial gauges on modulus of elasticity calculations. Authors claim that because of anisotropic character of wood, extrapolation to the same wood species or different species is not possible.

JIANG *et al*. (2014) investigated compression strength and modulus of elasticity under compression parallel to the grain (MOEC) of oak wood at ultra-low and high temperatures. The species used in the study was *Quercus mongolica.* The authors found out that with decrease of temperature compression strength and modulus of elasticity when compressing are raising. The correlation between compression strength and temperature and MOEC and temperature created a linear model and a polynomial model, respectively. Therefore XAVIER *et al*. (2011) carried out stereovision measurements on evaluating the modulus of elasticity of wood by compression tests parallel to the grain. The investigated specie was maritime pine (*Pinus pinaster* Ait.*)*. Stereovision measurements occurred to be beneficial, because an average value was less sensitive to the material heterogeneity since it could be calculated basing on distance covering several annual growth rings.

ARRIAGA-MARTITEGUI *et* al. (2008) examined the characteristic values of the mechanical properties of radiata pine plywood and the derivation of basic values of the layers for a calculation method. The general result of the study showed that strength values increase as the thickness increases, what is most clearly seen by bending strength. This phenomenon has been also confirmed by SYCZ and KOWALUK (2019). Radiata pine wood performed higher shear strength than spruce. Shear strength value is not affected by the number of layers.

GUNGOR *et al.* (2006) carried out a research on technological properties of wingnut wood and characteristics of plywood from windnut wood. As regards air-dry density of the specimens for 11.6 mm thickness was 0.53 g/cm^3. The values of bending strength (parallel and perpendicular), MOE (parallel and perpendicular), bonding strength values equalled 59.6, 37.5, 5617, 3358 and 1.9 N/mm^2, respectively. Comparing these results with values of some major species, it turned out that values found for wingnut plywood were similar to those of 12 mm-thick plywood made from *Fagus* spp. and *Pinus* spp.

CHOI *et al*. (2018) analysed mechanical properties of cross-laminated timber (CTL) with plywood using Korean Larch. The Authors examined hybrid wooden-core laminated timber (HWLT) made from existing CTL and plywood. Species tested as plywood in the study was Korean Larch (*Larix kaempferi* Carr.). The lumbers for the lamina were made from North American Douglas fir (Shindaerim Sawmill, Incheon, Korea). There were two different numbers of plies (3-ply and 5-ply) manufactured. As regards properties of HWLT and plywood itself, the MOR as well as MOE results were higher for 3-ply plywood than for 5-ply plywood. While the number of plies increased, plywood's as well HWLT's bending strength decreased.

LEE (1983) examined the effect of CCA-treating and air-drying on the properties of southern pine lumber and plywood. The study showed that CCA-treatment significantly increases the hygroscopicity of tested materials. Glueline shear strength, MOE and MOR of CCA-treated southern pine plywood were reduced by about 10% - the modified plywood has a 9.8% MOE reduction and 11.5% MOR decrease. DIESTE *et al*. (2008) carried out a study on physical and mechanical properties of plywood produced with 1.3-dimethylol-4.5-dihydroxyethyleneurea (DMDHEU)-modified veneers of *Betula* spp. and *Fagus sylvatica* L. It turned out that the modified samples for both species were more dimensionally more stable than untreated ones. MOE as well BS occurred to stay unaffected by the treatment with DMDHEU. It means that modified plywood was able to absorb less energy than untreated samples. Brinnel test showed that the DMDHEU-modified plywood was harder than before the modification.

TENORIO *et al*. (2011) made comparative study on mechanical and physical properties of laminated veneer lumber and plywood panels made of wood from fast-growing *Gmelia arborea* trees. It turned out that the properties of LVL as well PW are comparable to those of solid wood with density of 0.60 g/m^3. However, the shear resistance of PW was longer than by LVL. The significant differences between mechanical properties of PW and LVL composed of *G. arborea* are due to the orientation of the veneer in the panels.

NORRIS *et* al. (1956) made a research on compression, tension and shear strength of yellow-poplar plywood panels of sizes that do not buckle. The tension tests of MOE of plywood performed at various angles to the face grain proved the theory of elasticity. As regards the compression test, MOE values lie between minimum and maximum values predicted by the theory of elasticity. It turned out that the widest specimen, the greatest MOE values is obtained. Accurate MOR value can be determined by means of three tension tests upon matched material: one perpendicular, one parallel and one at 45^o to the direction of the face grain. The widest specimens performed the highest compressive strength values.

CURRIER (1962) examined the compression of douglas fir plywood in 5 various hot-pressing cycles. The Author tested soft-grained as well hard-grained veneer. The study showed that plywood panels manufactured with lowered pressure resulted in decreasing the compression strength when compared with plywood produced under normal pressure of 175 psi. Reduction in compression ranged between 26 and 57%, the average value equalled 39% of that in plywood pressed with 1.2 MPa. Permanent compression of panels bonded with blood-resin glue was less than that of plywood bonded with either exterior- or interior-phenolic glue. What is more, hard-grained veneer compressed less than soft-grained veneer while hot pressing, however it retained more of the compression during the recovery period.

SHI *et al*. (1999) carried out a research on the effect of the addition of polymer fluff to wood furnish on the mechanical and physical properties of wood fibreboard. As a binder, the Authors used polymeric diphenylmethane diisocyanate (PMDI) resin. The results showed that smaller fluff particle size determines higher IB, but lower WA and TS. The IB of fibreboards decreased linearly with increasing fluff content. The MOR and MOE of the composites decreased linearly with changes in fluff content from 0 to 60 percent. Also OSMAN and AKGUL (2020) examined mechanical and physical properties of medium density fibreboard after chemical modification. Three different solutions of formaldehyde glue were prepared with calcite share respectively: 3% (20 kg/m^3), 6% (40 kg/m^3), and 9% (60 kg/m^3). The species used in this study were: Beech *(Fagus orientalis* L.*)* from Duzce province forestry, Oak *(Quercus robur* L.*)* from the West Black Sea region and pine *(Pinus sylvestris L)* from Bolu province. Boards with density of 500, 700 and 850 kg/m^3 bending strength (MOR) properties decreased as the filling amount increased. The IB of MDF with density of 550 and 700 kg/m^3 decreased while the filling amount was increasing. Increasing in calcite minerals share resulted in reducing the values of MOE. The Author suggests filling MDF with 3% and 6% calcite minerals.

BÜYÜKSARI *et al*. (2012) examined mechanical and physical properties of medium density fibreboard panels laminated with thermally compressed veneer. Different levels of pressure (4 MPa and 6 MPa in time of 8 min.) and temperature (150^{o}C, 180^{o}C and 200^{o}C) were used by laminating. The species of rotary peeled veneer samples was European beech (*Fagus orientalis* L.). Both MOE and MOR of the specimens increased with increasing pressure and press temperature. Also thickness swelling was influenced by increased pressure, however differences in press temperature did not result in changes of dimensional stability. PARK and KIM (2001) also examined medium density fibreboard (MDF) performance. The Authors used four different sources of wood-fibres from Italian poplar, Eucalyptus, hemlock as well mixed species fibres. The influence of fibre characteristics on the MDF-performance bonded with both phenol-formaldehyde (PF) and urea-formaldehyde (UF) adhesive was tested. Fibre characteristics included: size distribution, fibre length, acidity and bulk density. The highest IB showed MDF panels produced using mixed species fibres. The lowest IB strength was observed in the MDF panel made from hemlock fibres. Regardless of resin type used in fibreboards, the biggest IB was examined by MDF boards made of mixed species fibres. IB strengths of MDF panels were strongly affected by the fibre acidity (pH) and by the internal mat structures resulting from fibre distribution and length. As regards MOR and MOE, all PF-bonded MDF panels had better MOE than UF-bonded boards. Fibreboards made of mixed species fibres showed highest MOR values, although the best MOE was performed by MDF panels from Italian poplar fibres.

XING *et al*. (2006) examined the medium-density fibreboard performance as affected by wood fibre acidity, bulk density and size distribution. It turned out that the higher the proportion of shorter fibres, the higher the bulk density is. The mechanical properties increased with alcaine buffering capacity. However, the increase of proportion of coarse fibres negatively affected mechanical properties of MDF panels. IB strength, MOR and MOE increased with increasing fibre bulk density. Moreover, IB strength was becoming higher while increasing pH values of fibres.

KAWASAKI *et al*. (1999) made a research on sandwich panel of veneer-overlaid low-density fibreboard. The dry MOE and MOR when measured in the parallel direction of sandwich panels with thicker veneers turned out to be superior. Both parameters examined in the parallel direction of boards overlaid with 2.0 mm thick veneer and with densities of 0.4-0.5 g/cm^3 were 40-60 MPa, and 5-8 GPa so two or four times as much as those of homogeneous fibreboards, respectively. As regards fibreboards with density of more than 0.35 g/cm^3 10% resin content being sufficient is required.

Most of mechanical properties of wood composites, like bending strength, modulus of elasticity, internal bond, screw withdrawal resistance etc., are tested due to the high significance from the end user point of view. The mentioned features are generally tested according to the standardized procedures. There is no standard for testing the compressive strength of particleboards, however, it could vary depending on several factors mentioned above. This feature of particleboards is very often neglected, but it has influence on the panels i.e. when the produced panels are stacked and stored in a few meters high packages. Since the compressive strength of the panels, especially located in bottom zone, may be exceeded by loaded upper packages, these panels are destroyed locally by separators or have a lower thickness. KOWALUK and JEŻO (2020) already investigated the impact of density on compression strength and MOEC for several particle board-types. This time Authors wanted to examine the influence of the mentioned factor on compression of different wood composite-types commonly used in the industry.

The aim of this research was to characterize the relation between contractual compressive strength, modulus of elasticity under compression and density of selected wood-based composites, by measuring the compressive strength of commercially - available panels of various density.

MATERIALS AND METHODS

Wood composites samples in ten different commercial types were prepared (Figure 1):

a) waterproof hardwood plywood,
b) softboard,
c) hardboard 5 mm thick,
d) hardboard 9 mm thick,
e) MDF laminated,
f) MDF raw,
g) OSB,
h) HDF,
i) coniferous plywood,
j) laminated particleboard 24 mm thick.

For each type there were 10 samples made. Modulus of elasticity by compression (MOEC), density, density profile and compression strength were measured.

Density and density profile

The density of every sample subjected further tests, has been estimated according to EN 323:1999 standard. As many as three samples of each panel variant with nominal size 50x50xthickness, mm^3, were used to measure density profile. After the measurement, the profiles were compared within one panel type, and most representative one has been taken to further analysis in refer to remaining panels. The study was carried out by using the X-Ray density analyzer DA-X (GreCon). The study was conducted at 0.10 mm/s speed and the sampling step was 0.02 mm.

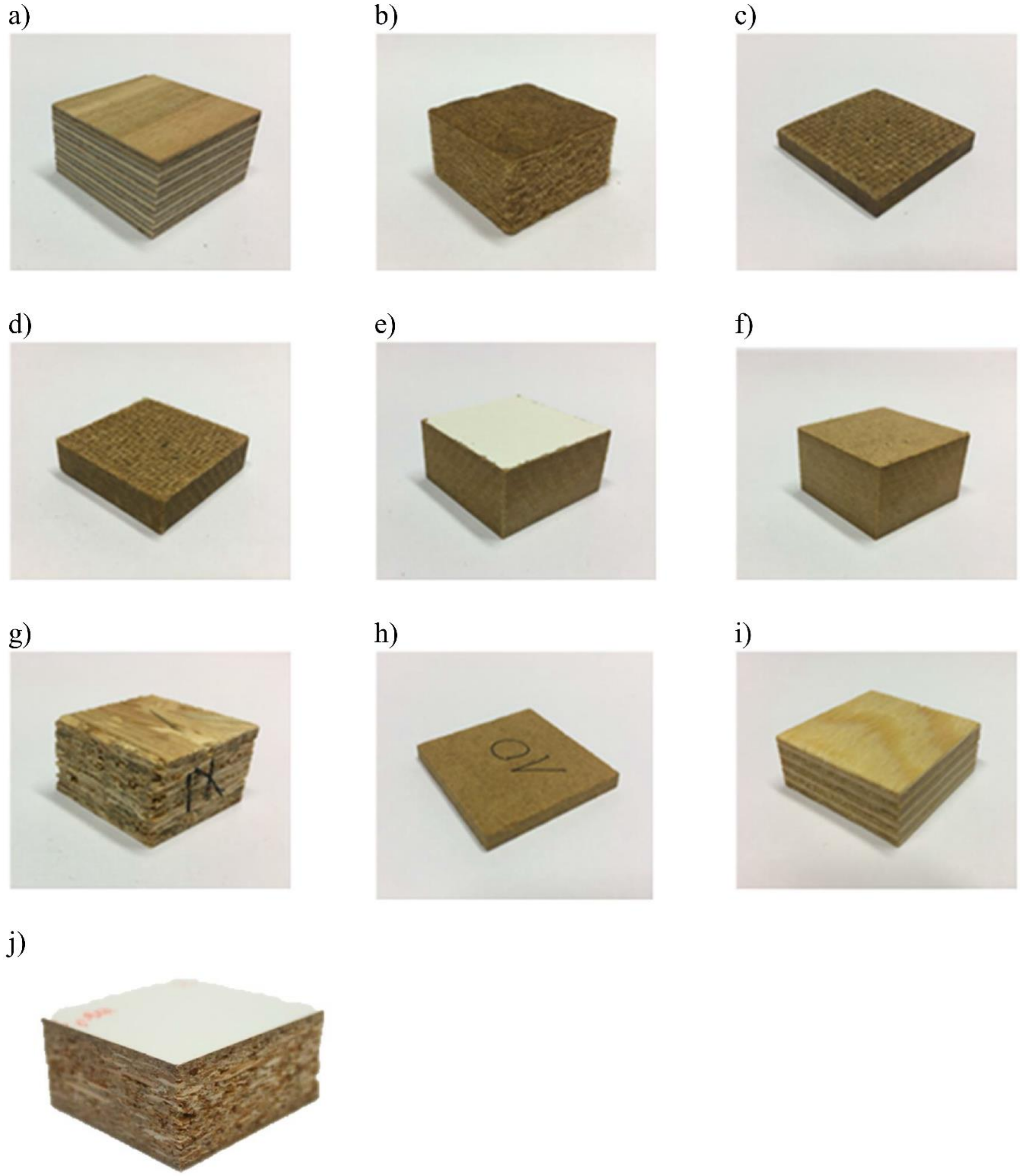

Figure 1. The pictures of the tested particleboards: a) waterproof hardwood plywood, b) softboard, c) hardboard 5 mm thick, d) hardboard 9 mm thick, e) MDF laminated, f) MDF raw, g) OSB, h) HDF, i) coniferous plywood, j) laminated particleboard 24 mm thick

Compression strength and modulus of elasticity under compression

For this study, ten samples of each variant were measured with the universal, computer-controlled testing machine. The deformation speed was set to reach the maximum load within 60±30 s, and the starting load was 0 N. Samples of nominal dimensions (a x b x t) of 23 x 23 x thickness, mm^3, were installed between flat, tiltable bottom surface and flat stable upper surface, both larger than sample surface, to provide the uniform compression on the whole panel. The above-mentioned sample size has been selected according to preliminary tests, to reach the correct load when pressing a wide range of tested particleboards beyond their elasticity zone. The strength was statically increased, till it reached the plasticity deformation zone (what was visible on the real-time plot and registered by computer). The compression strength [N/mm^2], here called also "contractual compression strength" has been calculated as a maximum load [N] registered in the elasticity zone (the "B" point in A – B zone on Figure 2) when pressing, referred to the sample surface a x b [mm^2]. The modulus of elasticity when compressing (MOEC) [N/mm^2] has been calculated by computer after the compression test for elastic deformation zone. The MOEC has been defined according to Jiang *et al.* (2014) by equation (1):

$$MOEC=((Load\ B-Load\ A)\times t)/(a\times b\times(Deflection\ B-Deflection\ A))\ [N/mm^2] \quad (1)$$

where: MOEC – modulus of elasticity when compressing (MOEC) [N/mm^2]; Load A, Load B – load values at A and B points (see figure 2) [N]; t – initial height of sample (panel thickness) [mm]; a, b – sample dimensions [mm]; Deflection A, Deflection B – deflection values at A and B points (see figure 2) [mm]

Statistical analysis

The obtained results (where applicable) were examined by means of analysis of variance (ANOVA), then subjected to the Student's test (α = 0.05), so that the statistically significant differences between the factors could be determined.

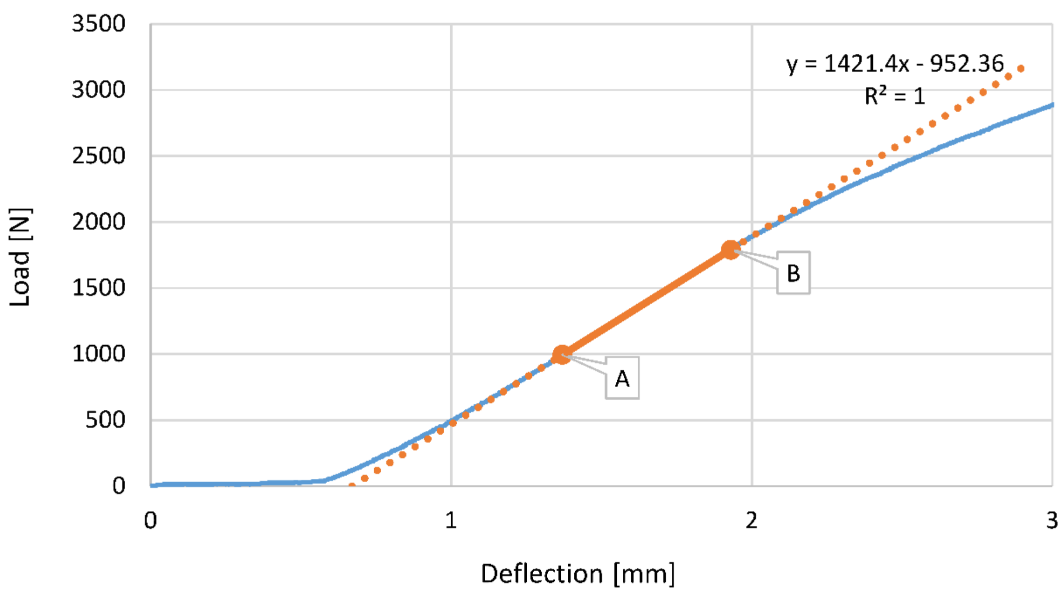

Figure 2. The load – deflection plot interpretation (A – B – elasticity zone; B – maximum load with elastic deflection) (Kowaluk and Jeżo 2020)

RESULTS AND DISCUSSION

Density and density profile

The results of density and density profile measurement have been presented on figure 3. Samples differed as regards their densities. Softboard had the lowest density of all (297 kg/m^3), while hardboard 5 mm performed the highest density (992 kg/m^3). Plywood performed complex profiles with repetitive shapes. Layers with lowest densities (about 700 kg/m^3 by hardwood plywood, 600 kg/m^3 by coniferous) appeared alternately with those of highest density-values (about 1200 kg/m^3 by hardwood, 1000 kg/m^3 by coniferous). Those can be caused by glue layers between veneer sheets. Hardboards showed homogenous density profiles throughout their thicknesses. All of the other examined samples had U-shaped profiles. Their densities were increasing while going to other layers. Particleboard laminated 24 mm had the biggest value of external layer (more than 1200 kg/m^3) which is caused by laminate. MDF raw, OSB and particleboard laminated 24 mm had middle layer densities close to each other, all around 600 kg/m^3. Outer layers of raw MDF equalled nearly 1000 kg/m^3, those of OSB - about 800 kg/m^3, while the lowest value occurred by softboard (around 500 kg/m^3). The average density of SB equalled about 300 kg/m^3.

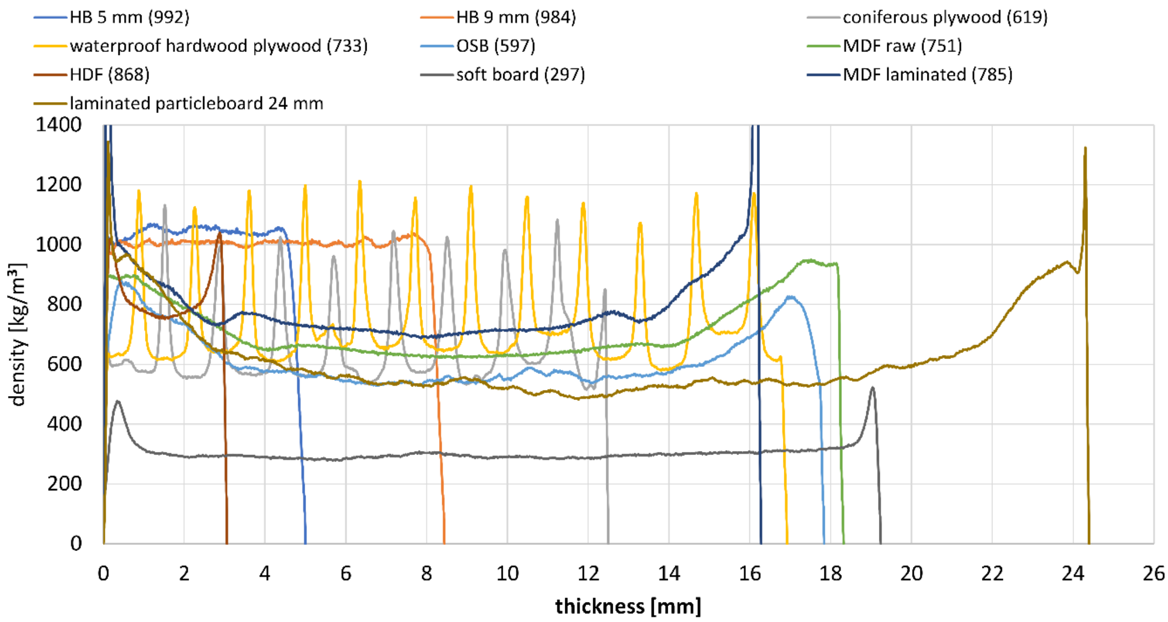

Figure 3. Density profiles of tested panels (average panel density in parenthesis)

Density share

The share of the specified densities of tested materials, defined as a specified density zone to layer thickness ratio, has been presented on figure 4. The assumption to create such a reference plot was to compare the further analysed results of the compression strength and MOEC with the share of the zones of specific density, namely low density. This should provide the information whether the mentioned mechanical properties of tested panels are depending on the low density zones. As it is shown, the panel with highest share of lowest density was SB. Figure 4. shows that the density of less than 300 kg/m^3 equals about 60% in SB. It is also worth to add, that in case of SB, the density share is very narrow and high peak, which means the density profile of SB is highly even and regular, if compared to remaining tested panels. On the other side, the largest zones with the highest density were found for panels HB 5 mm and HB 9 mm. Hardboards, both 5 mm and 9 mm performed the density of about 1000 kg/m^3 with a share of over 60% and about 45%, respectively. Second composite as regards high density share was HDF with more than 30% of density of over 700 kg/m^{3}The remaining panels, according to ascending share of the density dominant share zone, can be numbered as: laminated particleboard 24 mm, OSB, hardwood plywood, softwood plywood, MDF raw, MDF laminated, HDF. The surface layers of MDF covered with laminate reached more than 3000 kg/m^3. A significant correlation between density share and performed mechanical properties when compressing were not observed. Both HB 5 and 9 mm had the biggest share of high density, however, they did not perform highest values of compression strength and MOEC. The highest compression strength has been observed by laminated particleboard 24 mm thick, but it had low share of high densities. The sample-part of 1000 kg/m^3 is due to laminate on panel surfaces. There are no reasons that laminate can affect any mechanical properties during compressing. Other samples showed different density shares of a significant range. However, their compression strength occurred to be of nearly the same value. HDF board with the highest share of density of about 800 kg/m^3 performed the second lowest MOEC value, whereas the highest one was observed by the OSB samples with the main density of the biggest share equalling about 550 kg/m^3.

To prove that the density did not have a significant influence on mechanical properties when compressing examined composites, three different panels of similar density but different structure have been analysed. The following are: OSB (596 kg/m^3), coniferous plywood (619 kg/m^3) and particleboard laminated 24 mm thick (630 kg/m^3). It has been observed that by the nearly the same density, the compression strength and MOEC values varied significantly. Even though OSB and plywood seemed to perform similarly when compressing, the laminated particleboard showed higher values than both other panels. This case will be further described and analysed, but what is essential at this point, density is not a crucial factor affecting mechanical properties when compressing panels of similar density and of different structures.

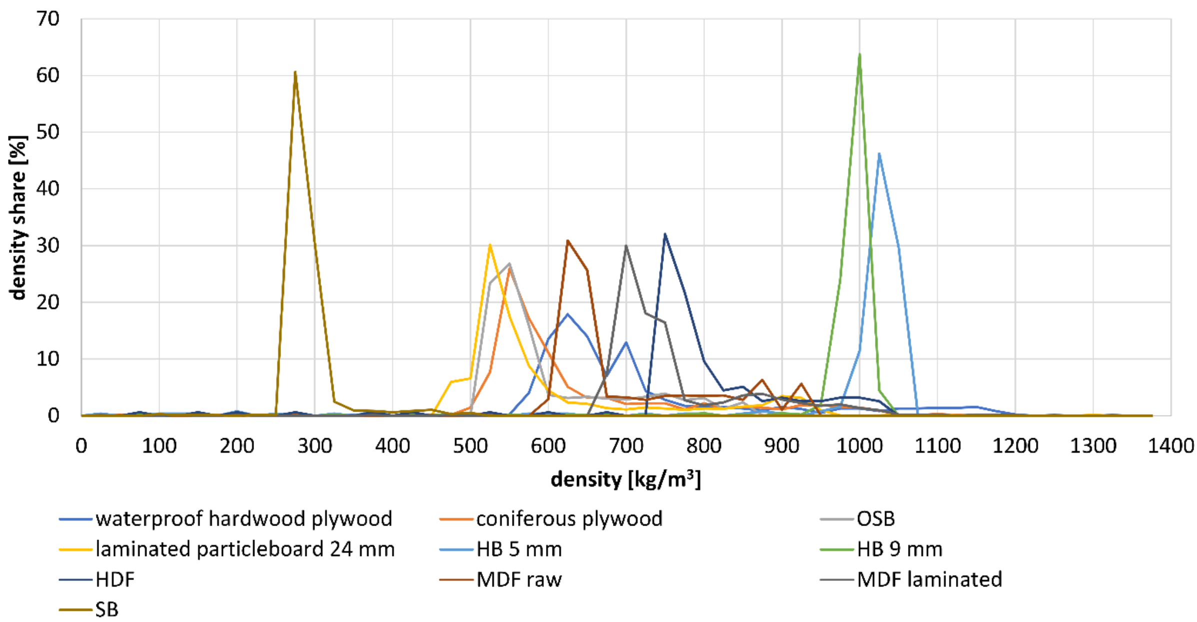

Figure 4. Density share of tested panels

Compression strength and modulus of elasticity under compression

The results of compression strength of tested panels have been presented on figure 5. The lowest compression strength occurred by softboard (0.87 N/mm^2), while particleboard laminated 24 mm performed the highest compression strength value (3.31 N/mm^2). As density profile shows, SB has the biggest layer of lowest-density. This may cause an easy deformation while compressing perpendicular to the plane. Excluding laminated particleboard 24 mm, which has the highest compression strength, the coniferous plywood, OSB, waterproof hardwood plywood, HDF, HB 5 mm as well as HB 9 mm had compression strength values close to each other, equalling about 2.80 N/mm^2. Despite a wide range of density values, the compression strength values differ from 2.72 N/mm^2 to 2.86 N/mm^2, what means the differences were in the range of about 5% of average value (2.80 N/mm^2) for these panels. It is worth to add, that the density range of these panels is from 597 to 992 kg/m^3, what means 49.44% of average density. It gives to little difference to be able to conclude that compression strength of examined composites is correlated to density. The measure of the quality of the fit of the linear model R^2 shows that density influences the compression strength only in 3.46%. The comparable results of compression strength have been also confirmed by statistical analysis, where the only statistically significant differences have been found between SB, laminated particleboard 24 and remaining panels.

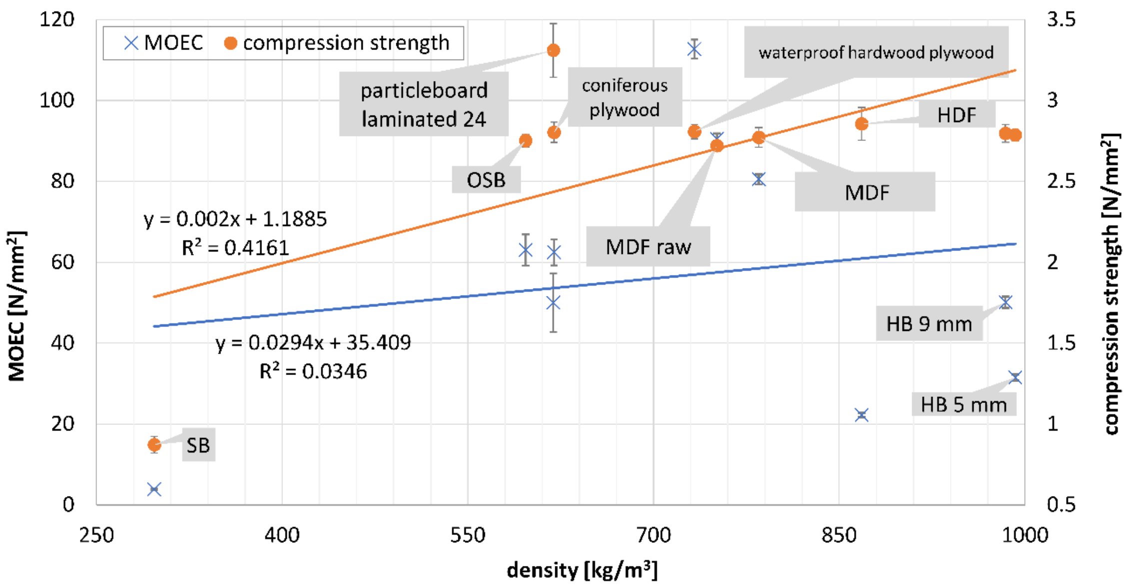

Figure 5. The compression strength and modulus of elasticity under compression (MOEC) of tested panels of various density

Modulus of elasticity under compression was increasing linearly with increase of density. The measure of the quality of the fit of the model R^2 shows correlation between density and MOEC of 41.61% which means little impact on the obtained values. Softboard performed the lowest values of MOEC (3.85 N/mm^2), exactly as by compression strength. The biggest value of MOEC was observed by the waterproof hardwood plywood (112.72 N/mm^2).

ARRIAGA-MARTITEGUI *et al.* (2008) in their studies on mechanical properties of radiata pine plywood obtained following results when measuring compression strength and MOEC perpendicular to the grain, respectively: 20.6 N/mm^2, 4610 N/mm^2 for plywood with thickness of 12 mm and 25.8 N/mm^2, 5833 N/mm^2 by 17 mm thick panel. Therefore, CHOI *et* *al*. (2018) as ultimate compressive strength (UCS) give 10.2 N/mm^2 and 8.0 N/mm^2 for 3-ply and 5-ply panels, respectively. YOSHIHARA (2010) examined 5-ply commercial plywood using two different methods: for L-type samples tested with IITRI method he obtained MOEC equalling 7.4 N/mm^2 and compression strength of 25.0 N/mm^2. The same method by T-Type samples gave results of 11.3 N/mm^2 and 15.8 N/mm^2 MOEC and compression strength, respectively. By end-loading test panels performed values of MOEC and compression strength equalling, in sequence, 7.5 N/mm^2 and 15.3 N/mm^2 for L-Type, 11.8 N/mm^2 and 24.0 N/mm^2 as regards T-Type. As it can be seen, the values registered by mentioned researchers are generally higher that here in the evaluated research results. It can be caused by different hardware setup applied in the compared research. However, KAWASAKI *et al*. (1999) as results of their studies on sandwich fibreboard panels received MOEC with value of 10 N/mm^2 for the panel with 400 kg/m^3 density, which is more comparable to results achieved here.

As it has been concluded by KOWALUK and JEŻO (2020), after KRZYSIK (1975), the following compression strength (contractual) across the fibers in intermediate (between radial and tangential) direction are characteristic: 4.31 N/mm^2 for pine (density 590 kg/m^3), 2.16 N/mm^2 for fir (density 500 kg/m^3) and 3.82 N/mm^2 for spruce (density 450 kg/m^3). The Authors have concluded that the mentioned in the literature results can be compared to those obtained by examining the particleboards, which are produced from coniferous species available in Poland. As long as the structure of particleboards is not as continuous as in solid wood, it has to be compensated by the higher density of tested panels.

It should be added, that in case of MOEC, the average values found in research have been more diversified. The statistical analysis show, that generally the differences between average values are statistically significant, excluding laminated particleboard 24 and OSB, as well as coniferous plywood and HB 9 mm.

CONCLUSION

According to the conducted research and the analysis of the achieved results, the following conclusions and remarks can be drawn:

1. There is not a significant linear correlation between density and compression strength of examined wood composites.
2. There is a weak correlation, equalling about 40%, between modulus of elasticity during compression and density.
3. Density share of examined composites turned out not to have any significant impact on mechanical properties when compressing the wood composites.
4. Comparing mechanical properties when compressing panels of similar density but different structures, it occurred that density can not be crucial when it comes to various structures.

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ACKNOWLEDGEMENT

Some actions to realize the mentioned research have been completed within the activity of Student Furniture Research Group (Koło Naukowe Meblarstwa) and Student Wood Technologists Research Group (Koło Naukowe Technologów Drewna), Faculty of Wood Technology, Warsaw University of Life Sciences – SGGW.

Streszczenie: Właściwości kompozytów drewnopochodnych przy ściskaniu w odniesieniu do gęstości. Celem badań była analiza umownej wytrzymałości na ściskanie i modułu sprężystości przy ściskaniu dziesięciu dostępnych na rynku kompozytów drewnopochodnych o różnej grubości, gęstości, strukturze i wykończeniu powierzchni. Zbadano również gęstość i profile gęstości badanych tworzyw. Badania wykazały, że brak jest istotnej zależności wytrzymałości na ściskanie oraz MOEC od gęstości tworzyw.

Słowa kluczowe: płyta wiórowa, płyta pilśniowa, sklejka, właściwości mechaniczne, ściskanie, MOE

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