Journal Pre-proof

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PII: S2352-7102(19)32549-5

DOI: https://doi.org/10.1016/j.jobe.2020.101460

Reference: JOBE 101460

To appear in: *Journal of Building Engineering*

Received Date: 20 November 2019

Revised Date: 25 February 2020

Accepted Date: 22 April 2020

Please cite this article as: Radosł. Mirski, D. Dukarska, A. Derkowski, Rafał. Czarnecki, D. Dziurka, By-products of sawmill industry as raw materials for manufacture of chip-sawdust boards, *Journal of Building Engineering* (2020), doi: https://doi.org/10.1016/j.jobe.2020.101460.

Radosław Mirski: Conceptualization, Methodology, Formal analysis, Data Curation, Writing - Review & Editing, Project administration, Funding acquisition. **Dorota Dukarska:** Validation, Formal analysis, Investigation, Data Curation, Writing - Original Draft, Visualization. **Adam Derkowski:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Writing - Original Draft, Visualization, Supervision. **Rafał Czarnecki:** Validation, Investigation, Formal analysis, Resources. **Dorota Dziurka:** Validation, Investigation, Writing - Review & Editing, Project administration.

By-products of sawmill industry as raw materials for manufacture of chip-sawdust boards

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Abstract: The paper investigated the possibility of using sawmill industry by-products, i.e. chips and sawdust as raw materials for the production of building wood-based boards. We prepared three-ply boards with the outer layer made from two types of pine particles (A and B) with different dimensions, and the core layer containing a mixture of chips and sawdust at 70 : 30 or 60 : 40 weight ratio. The boards also featured different core layer (CL) to outer layers (OL) ratio of 70 : 30 or 60 : 40. The study demonstrated that unprocessed by-products of mechanical woodworking in the form of chips and sawdust are valuable raw materials for the production of wood-based boards. Irrespective of CL : OL ratio, the boards with the best properties were those with outer layers made of microparticles larger than the ones used currently in particleboard manufacture and with core layers containing 70% of chips. The highest bending strength, modulus of elasticity and dimensional stability of board was noted for CL : OL ratio of 60 : 40, while the highest internal bond was achieved for CL : OL ratio of 70 : 30. These boards may be used as as non-structural elements intended for construction industry and interior decoration.

Key words: by-products, wood-based boards; chips; sawdust; strength; dimensional stability

1. Introduction

Numerous research centers have been for years investigating the possibility of producing wood-based boards in which wood is replaced with alternative materials, such as agricultural biomass or fast growing trees [1-7]. However, currently the basic material used in particleboard and fiberboard industry is still wood, very often in the form of by-products from mechanical woodworking. It is uncontaminated material, easily processed into particles or fiber pulp for further production of appropriate boards. The use of post-processed wood has been on the increase for several years, as its supply constantly grows with dynamic development of the wood industry and demand for wood-based products. The form of the material is highly variable (windows, door, constructional elements, packaging or broken furniture), and it often contains other materials, such as glass, metals or plastics and is covered with chemicals, such as adhesives, paints, varnishes or wood protection products [8, 9]. Nevertheless, industrial practice and research publications indicate that implementation of an appropriate segregation, purification and fragmentation methods allows for obtaining perfectly valuable raw material for the production of wood-based boards [8, 9, 10-13].

From economic and technological perspective, the most rational approach is to use materials from primary wood processing, mainly in the form of chips and sawdust that are not further processed. This is the solution most often adopted by the energy sector but rarely ever by the wood-based industry. One of the few examples of its use are chip-cement boards, utilized e.g. in building construction involving stay-in-place formworks. Despite having been on the market since the 1960s, these boards are still extensively studied. The aims of these studies are primarily to reduce the board density, to improve their thermal and acoustic properties while maintaining advantageous mechanical properties, to increase bonding on the wood-cement interface by chemical modification of wood raw material and to determine the impact of various factors on their sorption properties [14-18]. An interesting idea is also the use of sawdust for the production of light mortars and concrete mixtures [19, 20].

In this study we decided to investigate the possibility of using by-products generated during mechanical processing of wood as a raw material for the production of a new type of wood-based boards, i.e. chip-sawdust boards bonded with a synthetic adhesive. Our solution will enable the use of the raw materials without their further processing, e.g. fragmentation necessary during production of particleboards or fiberboards, and manufacture of final products of full value on the spot of the raw material generation. It will also help to reduce the costs of transport and storage of the raw materials and will make the process of board production considerably less expensive.

Considering the above, our aim was to examine the possibility of using unprocessed by-products of the sawmill industry to prepare chip-sawdust boards with good physical and mechanical properties enabling their successful use in the construction industry and interior design. Our primary objective was to determine the effects of the raw material composition and cross-section structure on the board strength and dimensional stability.

2. Materials and methods

2.1. Materials

Raw materials in the form of wood chips and sawdust were obtained from the Koszalińskie Przedsiębiorstwo Przemysłu Drzewnego Szczecinek S.A., a branch in Kalisz Pomorski, which is one of the largest sawnwood producers in Poland. Wood particles (microparticles) were obtained in industrial conditions from the manufacturers of wood-based boards. Moisture content of the chips and sawdust reached 5%, and of the particles 7 ± 0.5%. Fig. 1 shows the raw materials used, and Figs. 2 and 3 present their fractional composition. Additionally, Table 1 contains dimensional analysis for all chip fractions. As evidenced by the

Fig. 1. Wood raw materials used for the production of chip-sawdust boards: a - chips; b - sawdust; c, d - particles of the outer layers, type A and B, respectively.

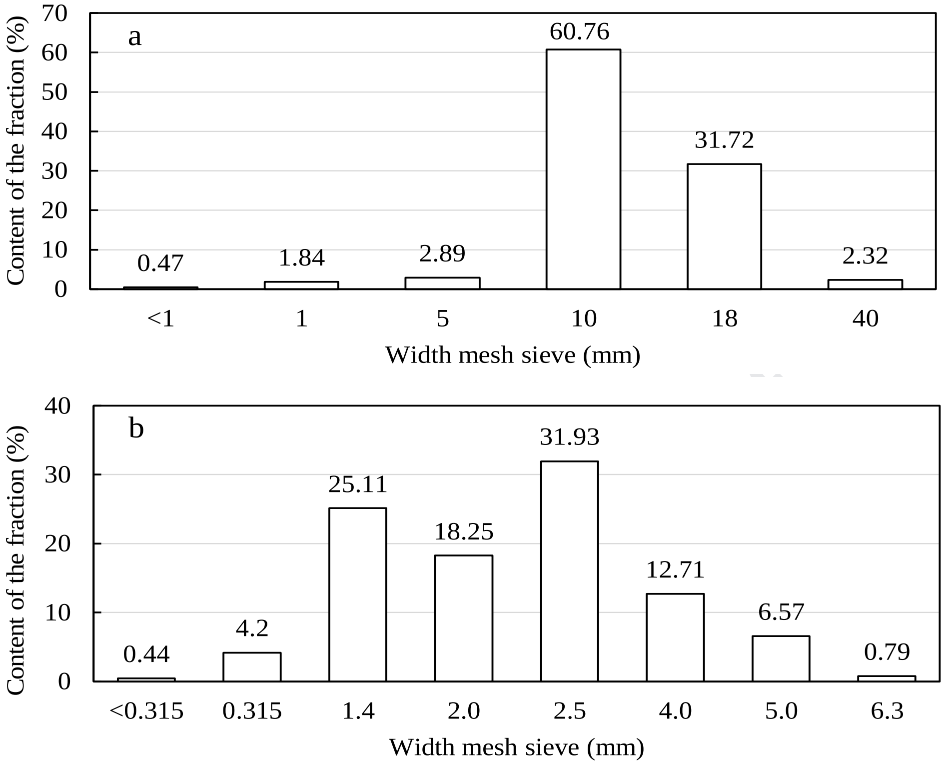

Fig. 2. Fractional composition of the core layer materials used in the manufacture of chip-sawdust boards: a - chips, b – sawdust.

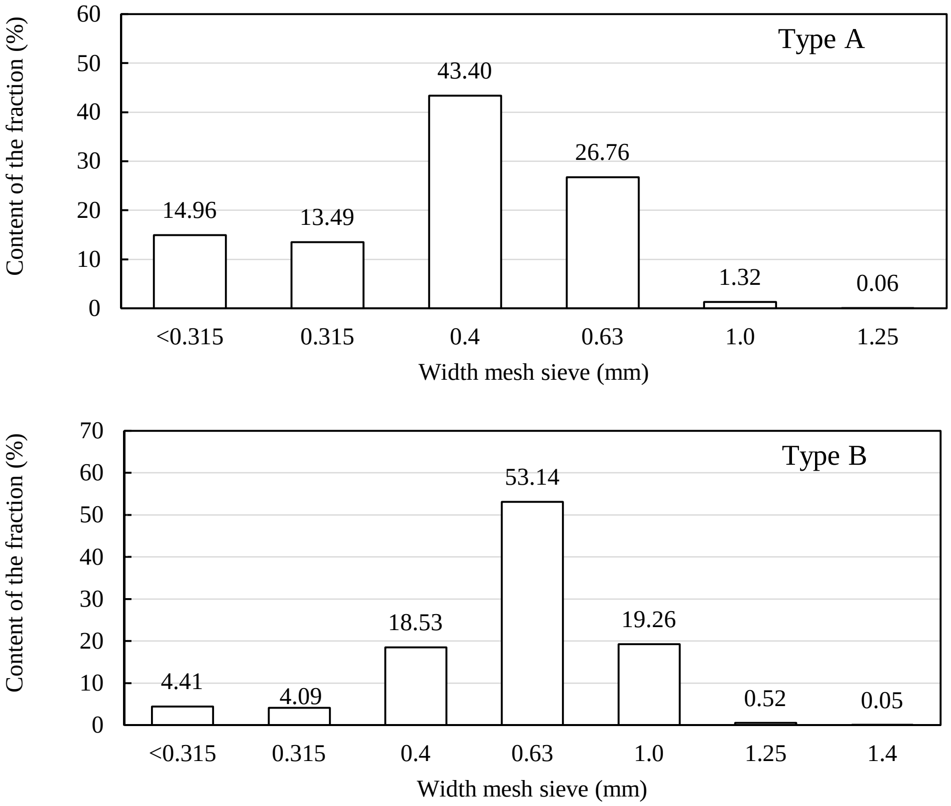

Fig. 3. Fractional composition of wood particles added to the outer layers of the chip-sawdust boards.

Table 1

Dimensional analysis of individual chip fractions.

Fraction (mm)	Length (mm)			Width (mm)			Thickness (mm)		
	Mean	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.
40	68.23 $^{9.84*}$	32.7	89.54	32.21 $^{13.32}$	15.45	58.43	15.21 $^{6.39}$	8.63	24.64
18	44.58 $^{18.24}$	27.63	83.58	26.54 $^{6.53}$	13.47	45.26	6.49 $^{3.36}$	5.17	11.48
10	26.79 $^{7.75}$	11.92	36.88	11.08 $^{5.58}$	2.56	21.41	4.20 $^{1.94}$	0.63	6.43
5	25.10 $^{3.49}$	24.09	31.00	5.85 $^{4.54}$	4.55	7.52	1.67 $^{1.71}$	1.08	3.93
1	19.66 $^{3.17}$	8.32	22.3	2.96 $^{0.76}$	1.07	4.22	1.39 $^{0.29}$	1.12	1.89

* – standard deviation

figures and the table, the studied wood chips were typical in terms of dimensional properties and fractional composition of the chips constituting sawmill waste that could be further processed mainly for the production of particleboards or fiberboards. The material defined as sawdust contained a fraction of splinter particles mainly of 4 mm or larger, and a finer fraction below 2 mm comprising wood dust, very fine sawdust, and fibrous particles. The fraction of 2 and 2.5 mm was a mixture of splinter particles and coarse sawdust, predominated by the latter. In turn, the analysis of the fractional composition of the outer layer particles showed that the fractions with the largest share were the 0.4 mm fraction for particles of type A and 0.63 mm for particles of type B. It can also be noticed that in the case of A particles the share of fractions below 0.4 mm was 13-15%, while for B particles it was only 4%. The B particles also contain a relatively high amount of the larger fraction, i.e. 1.0 mm (19.26%).

As an adhesive we used melamine-urea-formaldehyde resin (MUF) from Silekol (Poland) with the following properties: solid content 69.1%, viscosity at 25 °C 435 mPa·s, density 1.293 g/cm^3, pH 7.84, gel time at 100 °C 172 s and miscibility with water 0.8.

2.2. Works method

The experimental chip-sawdust boards were produced in laboratory conditions. Their outer layers (OL) contained two types of pine particles with different dimensions (A and B) (Figs. 1c and 1d), obtained during industrial machining. The core layer (CL) contained a mixture of wood chips and sawdust at a weight ratio of 70 : 30 or 60 : 40. Additionally, the experimental boards featured different proportions of core to outer layers. Table 2 presents all variants and symbols used to mark the investigated boards.

Table 2

Variants of the experimental chip-sawdust boards.

Variant	CL : OL ratio* (%)	Outer layers		Core layer	
		Wood particles type	Thickness of layer (mm)	Chips : sawdust ratio (%)	Thickness of layer (mm)
AA	70 : 30	A	3.8 (1.15)**	70 : 30	19.7 (1.28)
AB	70 : 30	B	3.7 (0.40)	70 : 30	20.3 (1.37)
BA	70 : 30	A	3.6 (0.57)	60 : 40	20.8 (1.20)
CA	60 : 40	A	4.7 (0.69)	70 : 30	17.8 (0.90)
CB	60 : 40	B	5.4 (0.98)	70 : 30	17.6 (0.83)
DA	60 : 40	A	5.3 (0.49)	60 : 40	18.2 (0.69)

* - core to outer layers weight ratio, ** - standard deviation

The board parameters were as follows: thickness 28 mm, density 600 kg/m^3, gluing degree (ratio of dry mass of resin to the dry mass of wood) of outer layers 12%, of sawdust 10%, and of chips 8%. The pressing was performed at 200 °C, at a unit pressure of 2.5 N/mm^2 for 25 s/mm of the final board thickness. Schematic diagram of chip-sawdust boards production is shown in Fig. 4.

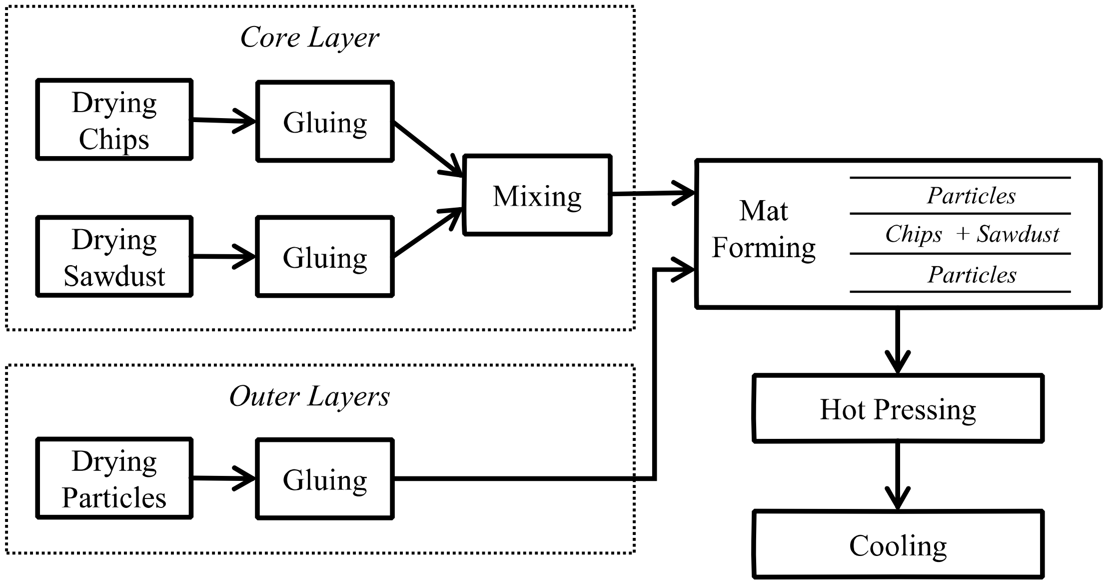

Fig. 4. Schematic diagram of chip-sawdust boards production.

The physical and mechanical properties of manufactured boards were tested according to relevant standards. Their three-point modulus of rupture (MOR) and modulus of elasticity (MOE) were determined as per EN 310 standard [21], using rectangular samples 610×50 mm^2 in size. Internal bond (IB) was figured out as described in EN 319 standard [22], and swelling after 2 and 24 h of soaking in water (TS) according to EN 317 standard [23]. In these two tests square samples 50×50 mm^2 in size were used. Together with thickness swelling there was investigated water absorption (WA) calculated on the basis of equation 1:

$$WA = \frac{m_2 - m_1}{m_1} \times 100 \qquad (1)$$

where WA is the water absorption (%), m_1 and m_2 are the sample weights before and after soaking (g), respectively. Each test was carried out on 10 samples.

The results yielded by physical and mechanical tests of the experimental boards were analyzed statistically using STATISTICA software v.13.1. Mean values of the parameters were compared in a three-factor analysis of variance – post hoc Tukey's test that identified homogeneous groups of mean values for each parameter for $p = 0.05$.

In order to illustrate the influence of the chip-sawdust boards structure on their properties, the work presents photos of selected variants of boards taken with a Moticam 10+ digital camera with the macro viewing tube and the MoticImages Plus 2.0 digital image recording system.

3. Results and discussion

3.1. Bending property of chip-sawdust boards

The tests of physical and mechanical properties demonstrated the greatest modulus of rupture (MOR 10.6 N/mm^2) in the boards with core to outer layers ratio (CL : OL) of 60 : 40, and containing larger wood particles of type B. Fig. 5 shows also positive effects of high share (70%) of the chips in the core layer, marked as CB variant. This was confirmed in the three-factor ANOVA that identified three homogeneous groups (a, b, c), and demonstrated the greatest significant differences only in the boards of this structure (homogeneous group c).

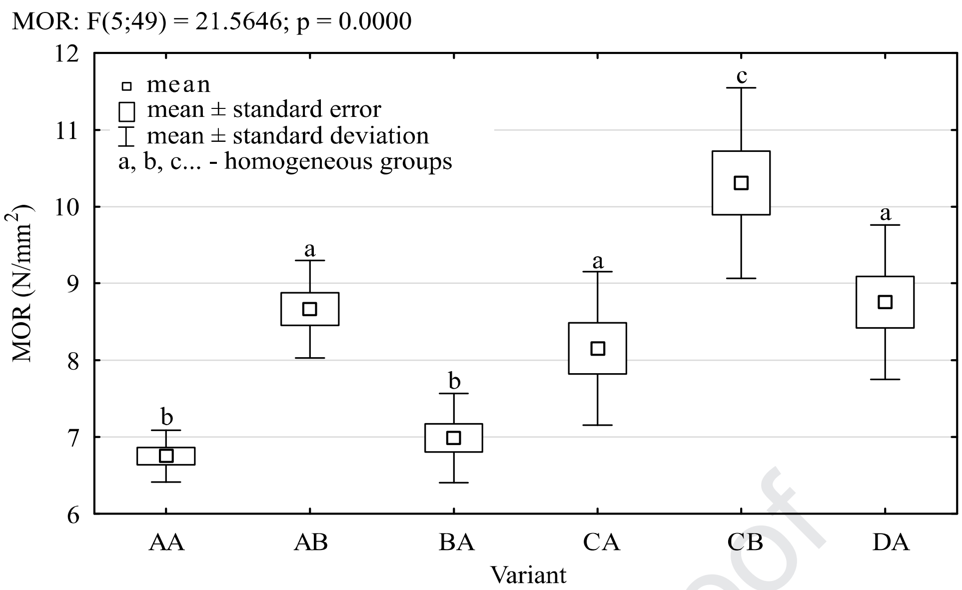

Fig. 5. Modulus of rupture of chip-sawdust boards.

Moreover, our experiments demonstrated that changing the CL : OL ratio to 70 : 30 (AB variant), that is lowering the thickness of the outer layers (Table 2, Fig. 6) reduced the board bending strength down to 8.7 N/mm^2, i.e. by about 18% when compared with CB board. Obviously the outer layers of multi-ply boards should compensate unevenness of the core layer. This seems particularly important in the boards whose core layers are made up of particles of highly variable geometry, i.e. different shapes and sizes. However, Fig. 6 shows that AB boards

featured not only reduced thickness but also uneven particle distribution and cross-sectional compaction. For this reason, the bending strength of AB board was lower than that of CB board. It should also be noted that the final thickness of the outer layers depends on both their weight share and compaction and deformability of both layers, that may also affect the bending properties of the boards [24, 25].

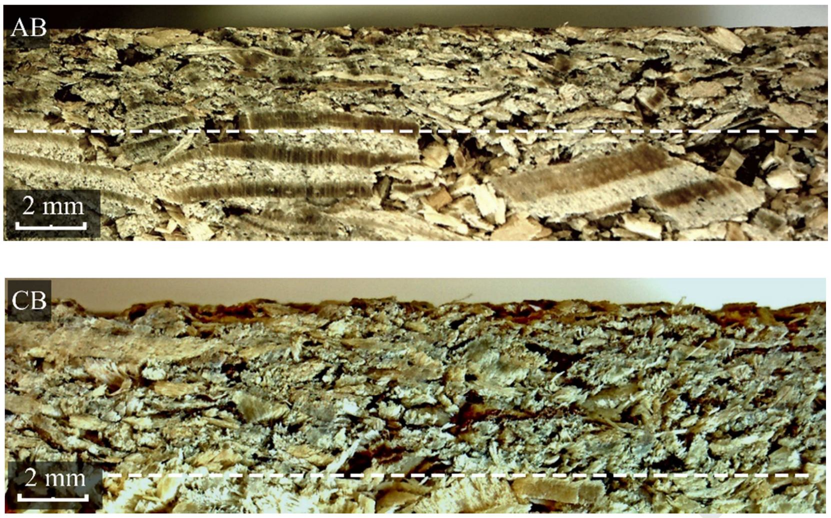

Fig. 6. Outer layers of chip - sawdust boards – AB and CB variant.

Making the outer layers of particles of considerably smaller size (type A) significantly decreased the board bending strength, no matter how thick the outer layers were. Although the share of the outer layers in CA and DA boards increased up to about 40%, MOR (homogeneous group a) dropped in relation to CB board by ca. 23% and 17%. As expected, AA and BA boards with 30% share of the outer layers showed the lowest bending strength of around 7 N/mm^2.

In general, MOR values reached relatively low levels. However, the investigated boards could be classified as so called thick boards, i.e. thicker than 25 mm. This is due to the fact that the resistance of core layer during mat compaction is lower in thicker than in thinner boards. For this reason, thicker board profile shows smaller density variations between the outer and core layers. Lower density of the outer layers accompanied by increased CL : OL ratio result in a decrease of bending strength and modulus of elasticity [24, 26, 27]. Undoubtedly, the density profile of the investigated boards was also shaped by their reduced density that reached approximately 600 kg/m^3. We may also assume that core homogeneity degree considerably affects other strength parameters. Using large chips in the core layer makes its structure highly heterogeneous (Fig. 7). It contains numerous empty spaces filled to different degree with sawdust (Fig. 8). This is due to e.g. considerable thickness of the chips that prevents their desired plasticization and compression during pressing. Nevertheless, the board with a 40% share of the outer layers made of larger wood particles and the core layer consisting of 70% chips (variant CB) meets the requirements of the EN 312 standard [28] in terms of bending strength for P2 particleboards, i.e. boards for interior fitments (including furniture) for use in dry conditions (the value required by the above standard for such boards of the thickness > 25 - 32 mm is 10 N/mm^2). Interestingly, MOR value for such a board (10.6 N/mm^2) differs only slightly from that required of P4 particleboards, i.e. boards capable of carrying loads in dry conditions, which according to EN 312 standard [28] should be 11 N/mm^2.

Our analysis of the chip-sawdust boards in terms of their modulus of elasticity (MOE) identified the dimensions of the outer layer wood particles as the key factor affecting this parameter. Such conclusion is confirmed by the results presented in Fig. 9. We found the highest values of MOE for the boards with outer layers made from larger particles (variants AB and

Fig. 7. Cross-section of a chip-sawdust board.

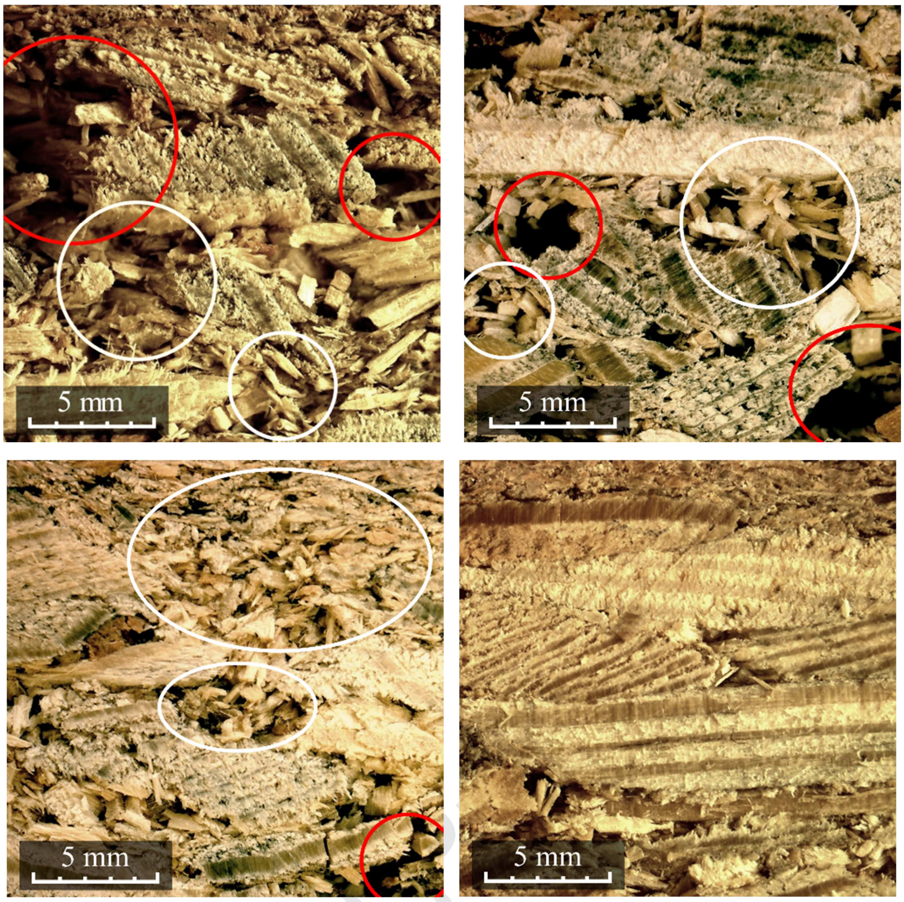

Fig. 8. Differentiation in the structure of chip-sawdust boards (red marks indicate empty spaces; white marks indicate spaces with sawdust).

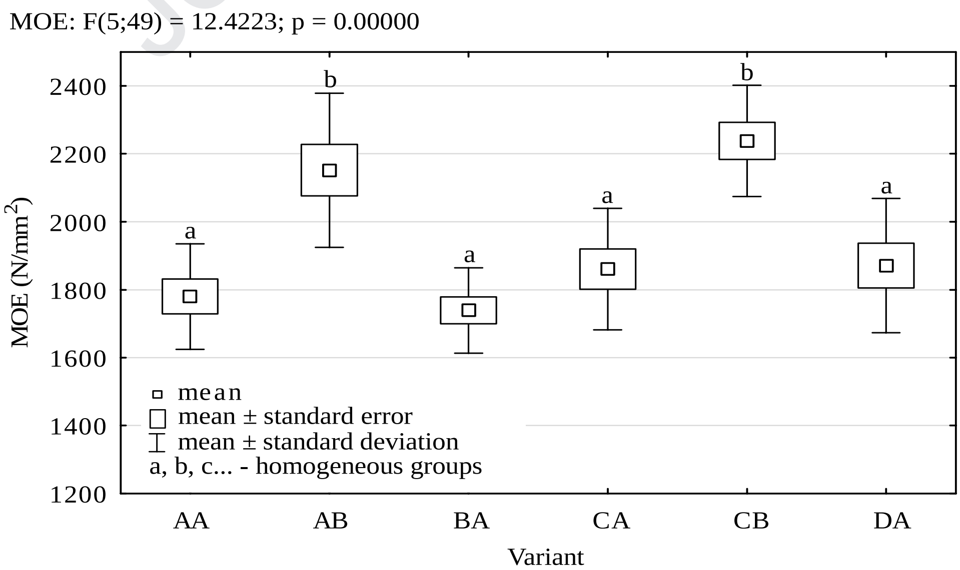

Fig. 9. Modulus of elasticity for bending strength of chip-sawdust boards.

CB), irrespective of the amount of chips and sawdust in the core layer and core to outer layer ratio. For these two variants post hoc Tukey's tests identified the same homogeneous group – b, while the other variants were classified into group a. This was confirmed by data obtained for the boards with the outer to core layer ratio of 70 : 30 or 60 : 40 and 70% share of chips in the core layers, and differing only in the particle size (variants AA and BA as well as CA and DA). Those boards showed higher mean MOE when we used longer and more slender particles, i.e. type B ones (Fig. 1d). This finding corresponds to the results published by other authors, e.g. Miyamoto et al. [29], Sackey et al. [30], Suffian et al. [31]; Cheng et al. [32]. Additionally, MOE for all tested variants was relatively high and fell between 1780 and 2240 N/mm^2. This allowed us to conclude that the experimental chip-sawdust boards AB, CA, CB i DA featured comparable or even greater rigidity than P4 particleboards (value required for boards with thickness > 25 - 32 mm is 1850 N/mm^2). The only exception were the boards AA and BA, in which modulus of elasticity was slightly below this standard and which can therefore be classified as P2 board intended for interior design, including furniture and dry conditions. As expected, the main factors affecting modulus of elasticity of the chip-sawdust boards included the shape and size of the outer layer wood particles, and as well as for MOR, the board cross section structure, i.e. outer to core layer ratio. Interactions of main effects depending by these analyzed factors presented in Fig. 10 confirm this conclusion. This is due to the fact that bending strength and board rigidity depend to a greater degree on the outer layers. Therefore, increasing their share in the board structure improves the bending strength and modulus of elasticity. Moreover, using longer and more slender particles (B) in the outer layers also enhances this type of durability.

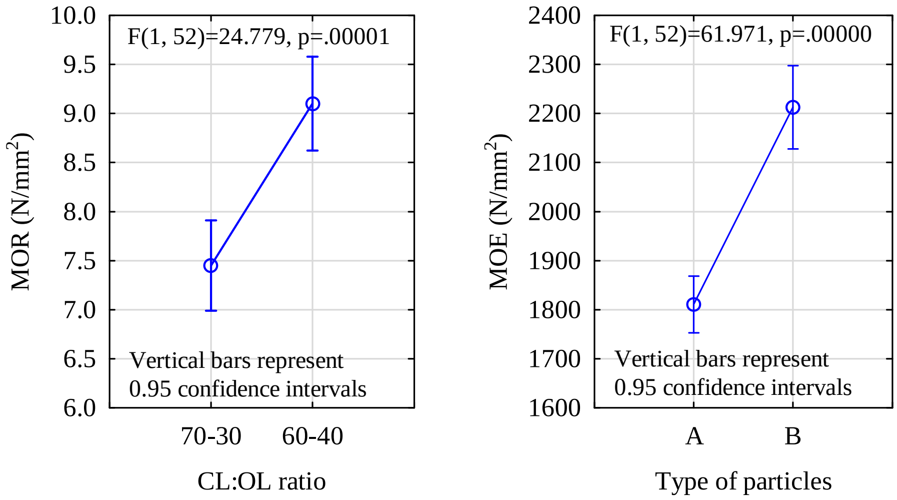

Fig. 10. Interaction diagram of modulus of rupture and modulus of elasticity of chip-sawdust boards depending on the analyzed factors.

3.2. Internal bond of chip-sawdust boards

Fig. 11 presents our results for internal bond (IB). They demonstrate that irrespective of the dimensions of outer layer particles, the greatest internal bond was achieved in the boards with greater proportion of the outer layers (i.e. CL : OL 70 : 30), composed in 70% of chips (variants AA and AB). Reducing the content of chips to 60% and increasing the proportion of sawdust to 40% (variant BA) resulted in a significant reduction of IB by ca. 25% (homogeneous group a). According to the literature, the presence of fine fractions in the core layer should increase the internal bond [31, 33, 34]. This is because that fine particles fill better the structure

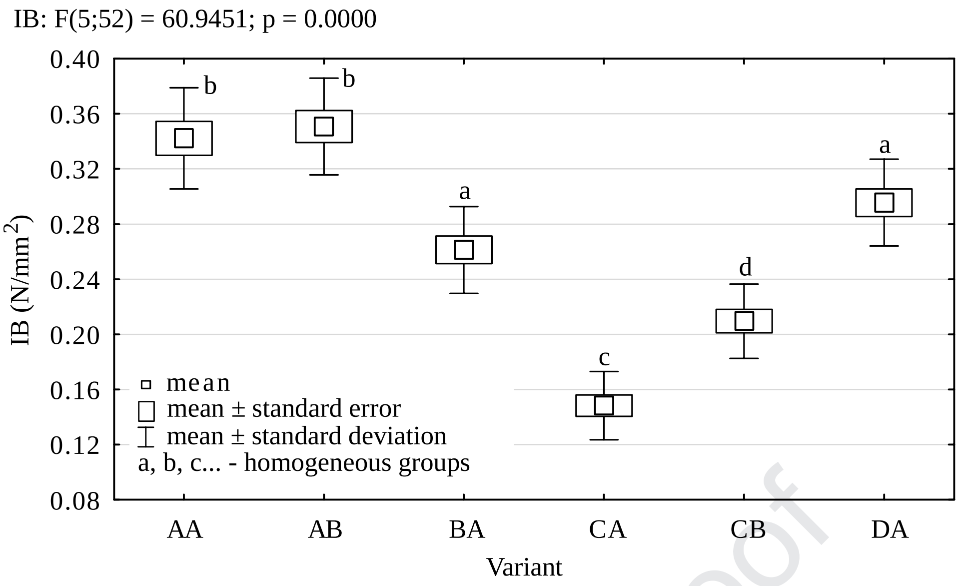

Fig. 11. Internal bond of chip-sawdust boards.

of the board, giving a more homogeneous structure with fewer empty spaces as can be seen in Fig. 12.

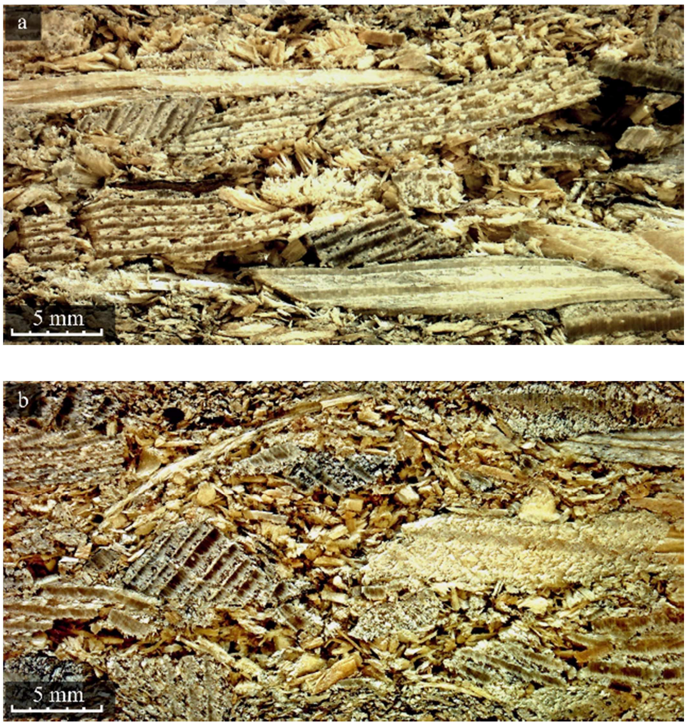

Fig. 12. Core layers chip – sawdust boards with chips : sawdust weight ratio: a - 70 : 30, b – 60 : 40.

However, as shown by Sackey et al. [30], the increase is limited by the share of the fine fraction. If its content exceeds 20%, the IB drops down. Additionally, the value of this parameter depends not only on the total content of fine particles but also on the proportion of particles of different sizes. This explains our results for IB in the investigated chip-sawdust boards. The sawdust we used constituted unsorted sawmill waste with highly variable fractional composition and high content of fine fraction and dust. Fig. 1b shows that their content (i.e. the fraction below 2 mm) was as high as 30%. Particles of this type, with considerable specific surface, absorb significant amounts of adhesive, thus limiting the amount and surface of adhesive-bonded joints between the chips. This reduces the quality of their loading and results in a decrease in internal bond. Further analysis of our outcomes for the other variants demonstrated no significant changes resulting from increasing the share of outer layers in the board cross-section (CL : OL 60 : 40) for the same chip to sawdust ratio of 60 : 40% (variant DA). This was confirmed by post hoc Tukey's test that classified BA and DA variants into the same homogeneous group a (Fig. 11). Raising the chip content to 70% significantly reduced IB from 0.29 to 0.15 N/mm^2 (variant CA). Similarly as for bending strength, this can be explained by heterogeneity of the board structure. Greater number and size of empty spaces in the board is known to reduce its bending strength and internal bond. We can therefore conclude that in terms of internal bond the boards with greater proportion of the core layer (AA, AB, BA) are comparable to P4 particleboards. These conditions are also met by DA board characterized by a smaller share of the core layer (CL : OL 60 : 40) made up in 60% of wood chips.

3.3. Water resistance of chip-sawdust boards

Table 3 presents water resistance parameters of the investigated chip-sawdust boards determined based on its thickness swelling (TS) and water absorption (WA) after 2 and 24 h of soaking in water. Interestingly, even after long exposure to water, TS was low and reached only 12 - 16%. This is an important observation, as we did not use any hydrophobic agents during the board production, which is an additional advantage of our solution in both economic and environmental terms. Such a result may be due to using MUF resin and large size chips. Big chips have relatively low specific surface, so they absorb less water and moisture [35, 36]. DA boards characterized by increased share of the outer layers made from fine particles (type A) and larger proportion of sawdust reached exceptionally high dimensional stability. This was evidenced by low TS values of 12.3% after 24 h of soaking in water. So poor swelling resulted from increased proportion of the outer layers in the board structure and the fact that smaller particles produce more homogeneous and compact structure that considerably limits water penetration into the core. Moreover, adding more sawdust to the core layer that contains large amounts of fine fractions increases the board homogeneity and limits water absorption [24, 29, 37]. This is confirmed by the results obtained in boards with smaller proportion of the outer layers (variant BA) or greater share of the chips (variant CA). Thickness swelling in such boards

Table 3 Water resistance of chip-sawdust boards determined by their swelling and water absorption after soaking in water.

Variant	TS (%)		WA (%)	
	2 h	24 h	2 h	24 h
AA	13.0 (0.91)* ab	13.9 (1.3) ab	80.3 (2.6) ab	87.0 (3.4) ab
AB	14.1 (1.1) bc	15.7 (1.8) c	80.1 (3.1) ab	90.9 (3.2) bcd
BA	13.2 (1.5) abc	15.5 (1.7) bc	86.6 (3.9) d	91.6 (4.0) cd
CA	14.5 (1.3) c	16.4 (1.3) d	82.2 (3.3) ab	94.4 (2.5) d
CB	12.1 (0.6) a	13.9 (0.6) ab	79.1 (2.2) a	85.6 (2.3) a

DA	10.6 (0.7) d	12.3 (0.9) a	83.1(2.6) bc	89.1 (1.8) abc

* - standard deviation; a, b, c… - homogeneous groups according to Tukey's test

after 24 h of soaking was by almost 30% greater than in DA variant. Nevertheless, chip-sawdust boards AA, CB and DA met high requirements in terms of swelling set out for P4 boards (the value required by EN 312 [28] is 15%). Reduced bending strength of the other boards (AB, BA

and CA) and their swelling values slightly exceeding 15% made them comparable only to P1 boards. Similar tendency was observed for water absorption that was the lowest in variants AA, CB and DA.

Summarizing all experimental results, it can be concluded that boards AB and CB showed optimal application properties. Their outer layers were made of larger particles (type B), and the core ones featured higher chip share (70%). The boards differed in their CL : OL weight ratio. In terms of modulus of elasticity and thickness swelling CB boards met the requirements for P4 particleboards and in terms of bending strength for P2 boards. However, their slightly reduced internal bond made them comparable to P1 particleboards, i.e. general purpose boards. AB boards met P4 board requirements for internal bond and modulus of elasticity but their lowered bending strength and slightly greater swelling meant that they should be classified as P1 boards. For the above stated reasons, these boards can be used in the construction industry and interior decoration as non-structural elements, e.g. internal doors [38]. Tests involving 28 mm thick industrial particleboards of rough and refined surface described by Mirski et al. [39] showed that this type of boards, and particularly AB boards, can also be used in manufacture of worktops and window sills. The authors found that the boards with refined surface showed much higher bending strength and modulus of elasticity than the unrefined ones.

4. Conclusions

1. Unprocessed sawmill industry waste in the form of chips and sawdust may serve as materials of full value for the production of wood-based boards with favorable physical and mechanical properties.
2. Their properties strongly depend on their cross-section structure, i.e. core to outer layer ratio, the content of chips and sawdust in the core layer and dimensions of the wood particles added to the outer layers.
3. The boards with the most advantageous properties were those with outer layers made of particles larger than microparticles used currently in particleboard manufacture and with core layers containing 70% of chips.
4. The highest bending strength, modulus of elasticity and the lowest swelling after 24 h of soaking in water was noted for the board with CL : OL ratio of 60 : 40, while the highest internal bond was achieved for the board with CL : OL ratio of 70 : 30.
5. Considering our study findings, it may be concluded that the boards of the above structure meet the requirements for P1 particleboards.
6. These boards may be used as base material for the production of boards intended for interior design, particularly joinery internal doors, window sills and countertops of working surfaces.
7. Our results are highly promising and may be used to design further studies aimed at developing a technology for manufacture of chip-sawdust boards with properties similar even to P4 particleboards.

Funding

This research was funded by the National Centre for Research and Development, BIOSTRATEG3/344303/14/NCBR/2018.

Acknowledgments

The authors are grateful for the financial support of the Ministry of Science and Higher Education program "Regional Initiative of Excellence" in the years 2019-2022, Project No. 005/RID/2018/19.

Conflicts of Interest

The authors declare no conflict of interest.

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Highlights

- Unprocessed sawmill industry by-products are full value raw materials for the production of a new type of wood-based boards.
- Chips and sawdust were used for the studies.
- Properties of chip-sawdust boards depend on their cross-section structure and on the raw material composition.
- Properties of these chip-sawdust boards are comparable to those of P4 type, i.e. boards capable of carrying loads in dry conditions.
- Chip-sawdust boards can be used in the construction industry and in the interior design.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

None