Influence of Strand Size, Board Density, and Adhesive Type on Characteristics of Oriented Strand Lumber Boards Manufactured from Pine Strands

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The influence of selected technological aspects was studied relative to characteristics of oriented strand lumber (OSL) boards manufactured from pine strands. Six types of boards were prepared, differing in the strand fraction size, density (700 kg/m^3 and 800 kg/m^3), and adhesive used to glue the strands in the core layer. The adhesives compared were melamine-urea-formaldehyde (MUF) and polymeric diphenylmethane diisocyanate (pMDI). The results showed that the OSL boards had good physical and mechanical properties, even though pine strands of diverse characteristics, particularly in terms of their length and width, were used for their production. The influence of strand size was clear in the results of the bending and elongation tests. Both for the bending test and tensile strength in a direction parallel to the wood grain, the properties were on average 20% greater for boards made of larger strands compared to those made of smaller strands. However, the latter demonstrated greater internal bonding strength (IB). The weakness of OSL boards made from small strands was their low modulus of elasticity, particularly when the board density was simultaneously reduced.

Keywords: OSL boards; Beams; Mechanical properties; Strand geometry

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INTRODUCTION

Engineered wood panels (EWP) can be classified as sheeting, structural, and insulating materials, and their intended use determines their physical and mechanical properties. Construction materials should have specific physical and mechanical properties and be much stronger than materials of other types. However, their density is frequently omitted, even though it is a decisive factor for the weight of finished components. Primarily, structural materials should transfer large loads. Strength and good mechanical properties are mainly achieved by transferring positive characteristics from wood to the material. Thus, wood used for production of these materials is usually of much higher quality than that used for production of other wood-based materials. Therefore, good mechanical properties in this type of material mainly result from appropriate quality and, in particular, the geometry of the wood strands used for their production (Geimer *et al*. 1975; Barnes 2000, 2001; Meyers 2001; Moriarty 2002). Wood fragments, usually free of any defects, are obtained by cutting or slicing and are formed in an oriented way. This production method significantly improves the mechanical properties of the manufactured materials (Harris and Johnson 1982; Geimer 1986; Canadido *et al*. 1988, 1990; Shaler 1991; McNatt *et al*. 1992; Suzuki and Takeda 2000; Barnes 2000, 2001; Nishimura *et al*. 2004; Chen *et al*. 2008). The importance of this effect has led to many years of attempts to model the strand layout within boards and the strand influence on the mechanical properties of the manufactured materials (Simpson 1977; Sharma and Sharon 1993; Steiner and Dai 1993; Dai and Steiner 1994a, 1994b; Dai *et al*. 2007a, 2007b, 2008; He *et al*. 2007).

Unfortunately, the improvement only applies for one direction of applied forces. Therefore, such a product can only be loaded in a precisely specified way to achieve its best properties. Materials of this type include oriented strand boards (OSB), laminated veneer lumber (LVL), scrimber (TimTeck), and oriented strand lumber (OSL), which is made from flaked wood strands with a high length-to-thickness ratio. Such materials, excluding OSB, are called "structural composite lumber," as they can be used both as boards and as beams, frequently replacing steel in construction.

Depending on the nomenclature accepted, OSL denotes a group of materials or a material made of wood strands. Formally, two materials are classified as OSL. The first, PSL (parallel strand lumber, registered name Parallam®), is made from veneer strands up to 8 feet long and 2 cm wide. Veneers are obtained using the peeling method. The second, LSL (laminated strand lumber, registered name TimberStrand®), is manufactured from wood strands up to 300 mm long, 25 mm wide, and 0.8 mm thick cut from hardwood logs of a small diameter and low density, usually from poplar, *e.g*., aspen (Meyers 2001). The strands are obtained by a similar means as during production of OSB boards. Sometimes the term OSL is also used for products manufactured in a way similar to LSL but from smaller strands. The shape of the wood fragments used to manufacture a given material is an important factor influencing the mechanical properties of wood-based materials. Although in industrial practice the shape of wood particles is irregular, except for veneer-based materials, they are still described by linear dimensions of a parallelepiped. For wood particles used to manufacture OSL in laboratory conditions, linear dimensions are within the following ranges: 78 mm to 142 mm long, 9 mm to 60 mm wide, and 0.55 mm to 0.75 mm thick (Preechatiwong *et al*. 2007; Beck *et al*. 2009; Taghiyari *et al*. 2016). Generally, the material used in the studies is of a uniform size fraction, and the thickness of the manufactured boards is less than 20 mm, mainly due to technical limitations.

This study focused on possibilities to manufacture OSL materials from pine strands of irregular shape. The aim of this work was to evaluate the influence of certain technological aspects on the properties of the OSL materials. The analyzed factors included the quality of the strands (determined as their average dimensions), the density, and the type of binding agent.

EXPERIMENTAL

Pine strands from industrial production of OSB were used in the study. Two fractions were selected for tests: a fraction retained on a sieve with a mesh size of 25 mm × 25 mm and a fraction passing through that sieve but retained on a sieve with a mesh size of 10 mm × 10 mm. Samples of approximately 1000 strands each were collected from the prepared batch of strands and used for quality verification, *i.e*., linear dimensions, slenderness ratio (λ), flatness (ψ), and width ratio (m). Melamine-urea-formaldehyde (MUF) resin (Silekol, Kędzierzyn-Koźle, Poland) and pMDI (polymeric diphenylmethane diisocyanate) glue (Ongronat® 2100, BorsodChem Group, Kazincbarcika, Hungary) were used to glue the strands. Before pressing, the strand moisture content was the same for both binding agents and was 4.9%. The gluing degree was 4% for pMDI and 6% for MUF. Ammonium nitrate (20%) was used as a curing agent for the MUF resin, added at 0.5% of the resin dry weight. The mat was formed manually, trying to place as many strands as possible along the longer side of a frame limiting the strands during formation. The manufactured boards were 40 mm thick, 380 mm wide, and 850 mm long. The mat was pressed at 200 °C at a pressure of 5 MPa for 1100 s.

Six types of boards were produced, differing in the fraction type (a, retained on 10 mm × 10 mm sieve; b, retained on 25 mm × 25 mm sieve), density (7, 700 kg/m^3; 8, 800 kg/m^3), and the adhesive used to glue the strands in the core (M, MUF resin; P, pMDI glue).

Samples were collected from manufactured boards to evaluate their properties. Bending strength and modulus of elasticity were evaluated for the samples according to EN 310 (1993), collected in a direction parallel to the board surface, with sample dimensions of 850 mm × 50 mm × 40 mm (board thickness). Bending strength and modulus of elasticity were measured for the samples, collected in a direction perpendicular to the board surface, with sample dimensions of 1450 mm × 40 mm (board thickness) × 100 mm. The evaluation was conducted for a three-point bending system. The distance between supports was 13 times the sample height (1300 mm). As only boards of the maximum length of 850 mm could be produced in laboratory conditions, the samples cut from the board for the bending strength test for a beam-type system were elongated with additional sections of solid pine wood. The pieces were joined using finger joints and PUR glue.

Internal bonding strength (IB) was measured according to EN 319 (1993). Board absorbability and swelling were determined according to EN 317 (1993). Sample shear strength was determined according to PN-59/D-04105 (1971). The shape and the dimensions of the samples collected for tests are shown in Fig. 1. Compression strength was measured according to PN-71/D-04102 (1979). Board samples of 20 mm × 40 mm (board thickness) × 80 mm were prepared for the tests. Tensile strength in a direction parallel to the board plane was determined according to PN-81/D-04107 (1981). Board samples of 8 mm × 40 mm (board thickness) × 240 mm were prepared for the tests. Sections of samples clamped in the tensile strength test machine were strengthened with 8-mm-thick plywood glued on both sides of the sample. Density profile measurements were made using the GreCon apparatus (GreCon, Hannover, Germany).

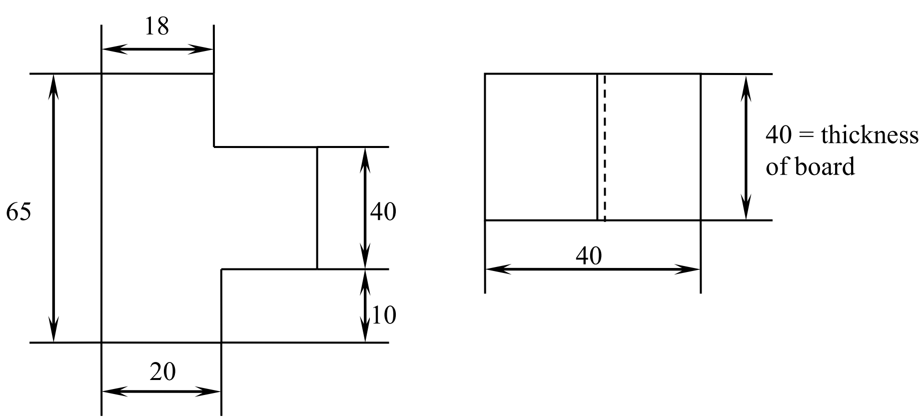

Fig. 1. Shape and dimensions (mm) of samples for shear strength test

Each test comprised 10 to 12 samples from each treatment combination, except for the static bending strength test and modulus of elasticity test. These two metrics were evaluated in six samples, and the density profile was measured for three samples. The test results were analyzed using Statistica 13.5 software (StatSoft Inc., Tulsa, OK, USA).

RESULTS AND DISCUSSION

Table 1 presents the dimensional characteristics of the strand fractions used in the study. Following sorting, two fractions were obtained, in which the distribution of strand linear dimensions did not follow the natural pattern. This was expected, taking into account how the strands were obtained and the sorting out of specific fractions. Long strands, of length greater than 110 mm, predominated in the fraction obtained from the sieve of the larger mesh (Fig. 2). The width of these strands showed a significantly greater distribution, demonstrating a negative value of kurtosis (K = -0.006252). Strand thicknesses for these two fractions gave the most similarly shaped distribution curves. However, the Mann-Whitney test demonstrated that strands in both distinguished fractions differed significantly, *i.e.*, the strands obtained from the larger sieve had greater linear dimensions, a higher degree of flatness, and a lower width ratio. The two fractions showed similar slenderness ratios, and this should translate into a similar ease in orienting the strands during mat formation.

Table 1. Dimensional Characteristics of Strands Used in the Study

Fraction Size		Length (mm)	Thickness (mm)	Width (mm)	λ	ψ	m
10 mm × 10 mm (a)	Mean	87.49^x	0.88^x	7.91^x	99.4^x	8.99^y	11.1^x
	Max	122.80	2.11	20.65	58.2	9.79	5.95
	Min	32.37	0.26	1.40	125	5.38	23.1
	Median	88.99	0.83	7.86	107	9.47	11.3
25 mm × 25 mm (b)	Mean	98.48^y	1.02^y	12.88^y	96.5^x	12.6^x	7.64^y
	Max	125.26	2.34	33.80	53.5	14.4	3.71
	Min	30.31	0.30	1.87	101	6.23	16.2
	Median	105.33	1.00	11.98	105	12.0	8.79

* Letters x and y mark statistical differences, where x < y, based on the Mann-Whitney U-test

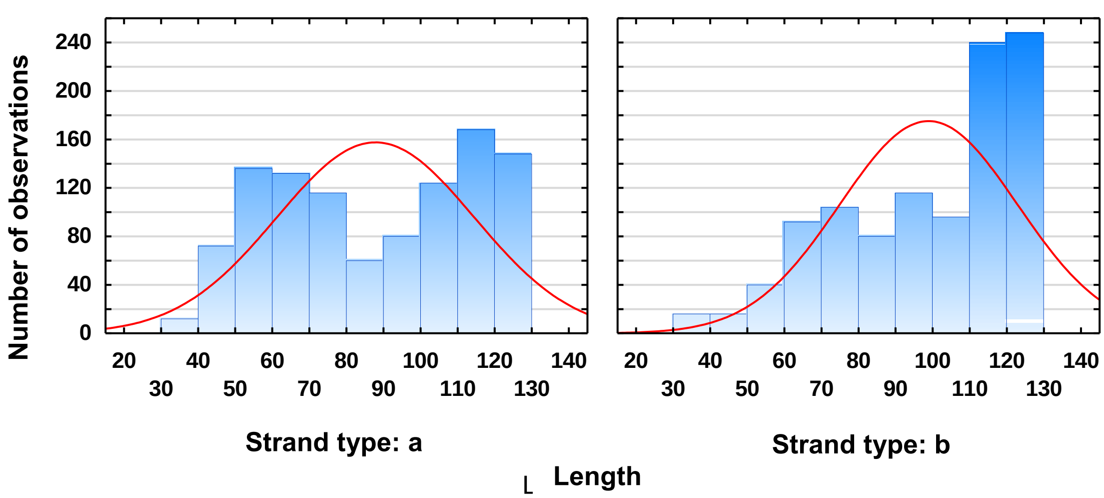

Fig. 2. Distribution of individual strand lengths for the analyzed fractions of strands

The adopted three-point system for the determination of the static bending strength and modulus of elasticity was based on the assumption that the strength of this type of beam should be approximately 60 N/mm^2 to 70 N/mm^2 (Chirasatitsin *et al*. 2005; Beck *et al*. 2009), which is relatively high. Therefore, as the distance of a micro finger joint from a loading nose increases, its participation in the load transfer decreases. By joining the OSL component with solid wood, homogeneity of the material is lost, but with this loading system that heterogeneity is relatively smaller. The majority of beams were destroyed near the center, although in some cases the sample was destroyed at a joint. If this happened, the destroyed fragment was cut off, and a micro finger joint was applied again. The beam elongation from 8 times its height to 13 times its height allowed for better determination of its strength during the bending test but negatively affected the evaluation of the modulus of elasticity. The created beam consisting of two materials changed its modulus of elasticity along its length but not across its cross-section, and consequently, the results could only be compared to each other, without referring them to materials evaluated in accordance with the standard. The static bending strength results were slightly lower than expected, although they were comparable to reference data for OSL or materials such as LSL or LVL. The greatest results for strength and modulus of elasticity were obtained for OSL with a density of 800 kg/m^3 and manufactured from large strands glued with pMDI, while the lowest values were obtained for OSL with a density of 700 kg/m^3 and manufactured from small strands glued with MUF (Table 2). Greater results were obtained for beams made of large strands, for which the values were more than 15% greater than for beams made of small strands. The greater density of boards increased their strength only by approximately 10%, while the beam strength was more than 20% greater for pMDI when compared with MUF resin. The post-hoc comparison after the one-way analysis indicated that three significant, though overlapping, groups should be distinguished: beams with a density of 800 kg/m^3 with strands glued with pMDI; beams of large strands glued with MUF or small strands glued with pMDI, but with a density of 700 kg/m^3; and OSL labeled as a7M, that is, beams with a density of 700 kg/m^3 made of small strands glued with MUF.

Table 2. OSL Characteristics Yielded by the Three-point Test

Symbol	MOR - Edgewise		MOE - Edgewise		MOR - Flatwise		MOE - Flatwise	
	X (N/mm^2)	V (%)	X (N/mm^2)	V (%)	X (N/mm^2)	V (%)	X (N/mm^2)	V (%)
b8P	57.3^{a}	6.3	6710^{a}	1.84	80.4^{a}	1.58	12350^{a}	2.1
a8P	50.2^{a,b}	10	5770^{a,b}	8.6	72.5^{b}	9.9	10890^{b}	7.9
b8M	45.3^{b,c}	4.5	5500^{b}	4.8	70^{b}	1.82	10930^{b}	2
b7M	44.1^{b,c}	6.1	5180^{b}	3.8	71.5^{b}	3.5	10960^{b}	4.2
a7P	40.4^{b,c}	6.7	5220^{b}	10	51.9^{c}	6.9	7950^{c}	6.2
a7M	36.4^{c}	10	4410^{c}	3.3	47.4^{c}	1.1	7530^{c}	3.6

Letters mark uniform groups determined with the Tuckey HSD test. MOR – modulus of rupture; MOE – modulus of elasticity; X – mean value; V – coefficient of variation.

Significantly greater values of static bending strength and modulus of elasticity were obtained when the manufactured OSL material was evaluated as boards. In that case, the static bending strength exceeded 70 N/mm^2, and the modulus of elasticity exceeded 10,000 N/mm^2, for the majority of variants. Furthermore, when small strands were used to manufacture the OSL, an increase in board density from 700 kg/m^3 to 800 kg/m^3 resulted in relatively large changes, reaching 40%. When larger strands were used, these changes were not perceptible. A similar effect was observed for a beam-type system (b8M ≅ b7M). Notably, material of this type is more frequently used as a beam than as a board. The gluing scheme adopted during this evaluation meant that the strands in the outer layers, transferring higher compressive and tensile loads, were glued with pMDI. This may be a reason why a7P and a7M boards did not differ statistically in their static bending strengths or moduli of elasticity.

One of the parameters indicating the adhesive quality and firmness of board materials is the internal bonding strength. The statistical analysis revealed that all three determined parameters strongly influenced this property of the boards (Fig. 3).

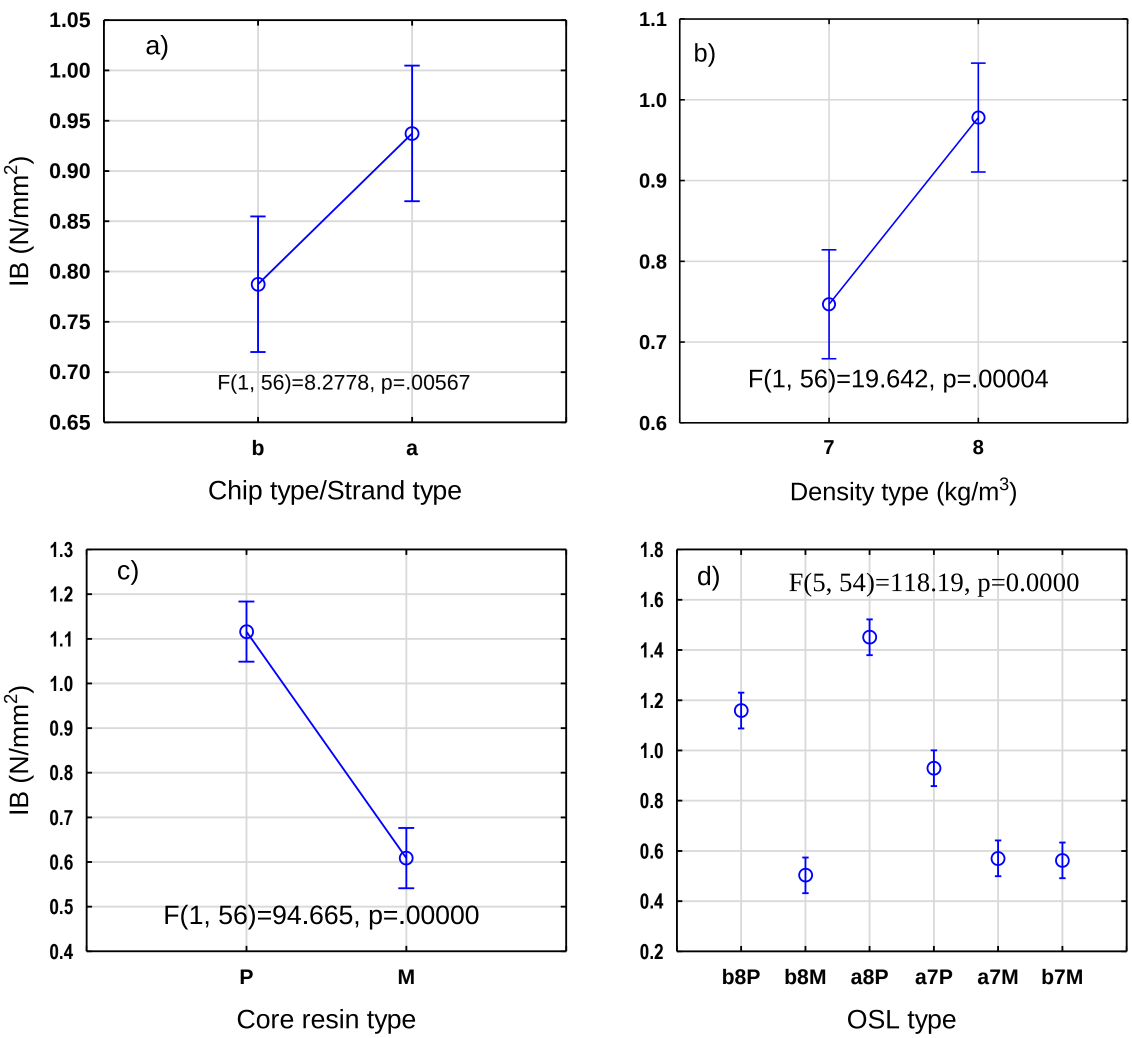

Fig. 3. Results of the three-way (a, b, c) and one-way (d) analyses for internal bonding strength

Distributions obtained for the three-way analysis showed that smaller strands significantly increased board strength, and this may possibly be related to their better arrangement within the board structure. Furthermore, the strength values strongly depended on the binding agent, as the results for pMDI were significantly greater (nearly 90%) than those obtained for MUF. An increase in the board density resulted in a greater increase in strength than the type of strands, although this increase was significantly less than for the type of the binding agent. However, the one-way analysis (Fig. 3d) showed that when MUF resin was used, the strength of that gluing was constant and independent of strand size or board density. Therefore, the relationships discussed above were considerably shaped by the behavior of boards with cores glued with pMDI. These changes were also slightly influenced by the density profile, as despite some differences in the densities of surface layers, the lowest densities were obtained near the center of the board thickness (Fig. 4). Boards with assumed densities of 700 kg/m^3 and 800 kg/m^3 had, respectively, actual average densities of 716 kg/m^3 and 816 kg/m^3 and minimum core densities of 615 kg/m^3 and 650 kg/m^3, a difference of 35 kg/m^3. The small strands were compacted in a slightly different way, and the OSL boards made of small strands had a core density approximately 40 kg/m^3 greater than that of the OSL boards made from large strands.

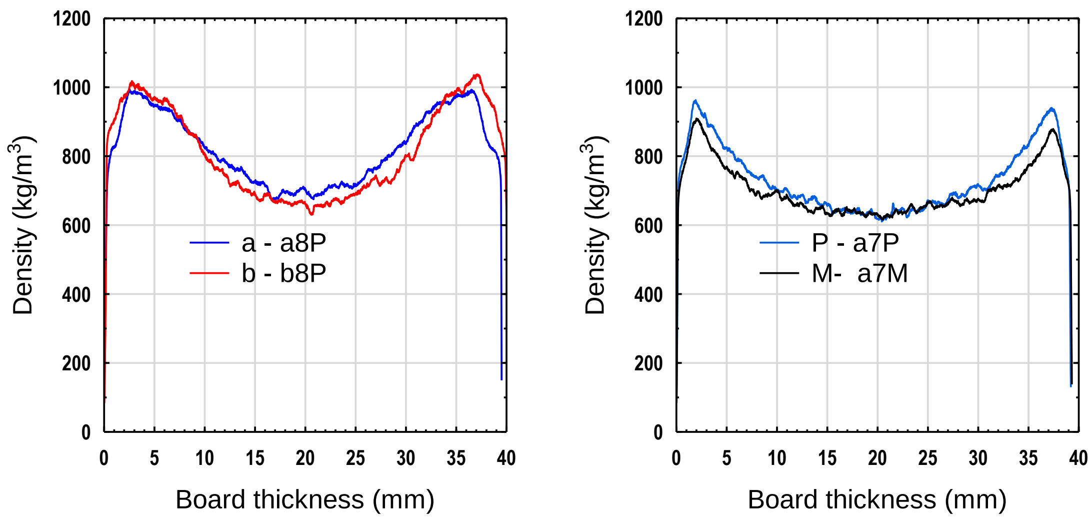

Fig. 4. OSL board density profiles

Compression strength (f_c) and tensile strength in a direction parallel to the plane (f_{tII}) are important characteristics of manufactured boards (Table 3). These properties are of particular importance because OSL is more frequently intended for use as beams rather than as boards. On average, the compression strength of the manufactured boards was approximately 60% greater than the tensile strength in a direction parallel to the board plane. Boards made of small strands showed a greater f_c to f_{tII} ratio than boards made of larger strands. Thus, boards made of smaller strands had lower tensile strength in a direction parallel to the plane than boards made of larger strands. The adhesive type also influenced the quality of the investigated boards. The results for boards glued with MUF resin were notably lower. The values for b8M and b7M boards, both those observed earlier (MOR, IB) and for compression and tensile strength, were similar.

Therefore, the influence of the board density was not seen here, and this result may indicate that, for this glue and the given conditions, the maximum strength was achieved. The shear strength of the experimental OSL boards was in the range of 3 N/mm^2 to 4.9 N/mm^2 (Table 3). This strength represents 30% to 50% of pine wood strength evaluated in defect-free laboratory samples and is comparable to, or even exceeds by approximately 25%, the strength of construction timber of the C24 to C50 classes. In general, these results for the compression, tensile, and shear strengths of the investigated OSL boards were similar to those reported in other studies, differing in type of wood (rubberwood)

(Chirasatitsin *et al*. 2005; Chotchuay *et al*. 2008) or strand length (Moradpour *et al*. 2018). Furthermore, in most of the studies concerning OSL, the authors used strands of selected specific length and width, and this significantly influenced the mechanical characteristics of the OSL boards. Swelling of the experimental boards after 24 h of immersion in water was relatively low, taking into account that no agents improving hydrophobic properties of the boards were used (Table 3). The swelling values ranged from 18% to 25%, and significant influence of the analyzed factors was difficult to determine. Although the statistical analysis showed that four levels of water-induced changes in board thickness can be distinguished among the discussed variants, it should be understood that OSL boards with a density of 800 kg/m^3 glued with pMDI showed much lower swelling than the other analyzed variants.

Table 3. Compression Strength (f_c), Shear Strength (f_s), Tensile Strength in a Direction Parallel to the Plane ($f_{t||}$), and Thickness Swelling after 24 h Immersion in Water

Symbol	f_c ||		$f_{t||}$		f_s		TS 24 h	
	X (N/mm^2)	V (%)	X (N/mm^2)	V (%)	X (N/mm^2)	V (%)	X (%)	V (%)
b8P	54.2^a	7.6	35.9^a	6.5	4.9^a	15.1	18.3^a	4.1
a8P	42.8^b	4.2	30.6^b	5.4	4.7^a	12.6	18.4^a	4.4
b8M	39.7^{b,c}	6.4	24.9^c	9.1	3.5^{c,b}	8.5	25.2^d	4.5
b7M	37.0^c	6.1	25.7^c	7.5	3.3^c	8.9	22.0^b	2.1
a7P	36.5^c	7.7	20.3^d	7.9	4.3^{b,a}	15.0	22.9^{b,c}	7.7
a7M	31.8^d	3.0	16.7^e	8.2	3.0^c	9.5	23.6^{c,d}	5.0

Letters mark uniform groups determined with the Tukey HSD test

CONCLUSIONS

1. The tested OSL boards showed good physical and mechanical properties, although pine strands of diverse linear dimensions, *i.e*., of highly varied length and width, were used for their production.
2. The influence of the strand size was clear in the results of the bending and elongation tests. The bending test results for the boards made of larger strands were approximately 15% greater than the results for the boards made of smaller strands. The tensile strength in a direction parallel to the plane was approximately 25% greater for larger strands; in a direction perpendicular to the plane, it was greater by a similar amount for smaller strands.
3. The weakness of OSL boards made of small strands was their low modulus of elasticity, particularly when the board density was simultaneously reduced.

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