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The influence of structure on selected properties of a lignocellulosic composite

KRYSTIAN SYCZ, GRZEGORZ KOWALUK
Department of Technology and Entrepreneurship in Wood Industry, Faculty of Wood Technology, Warsaw University of Life Sciences – SGGW, 159 Nowoursynowska St., 02-787 Warsaw

Abstract: *The influence of structure on selected properties of a lignocellulosic composite*. As part of the research, the influence of the number of layers and the structure of plywood on selected physico-mechanical properties was determined. The scope of work included: bending strength and modulus of elasticity, resistance at axial removal of screws and density profile. The influence of thickness increase on selected properties of plywood was confirmed. Flexural strength decreases by 60%, modulus of elasticity by 71%. As the number of composite layers increases, the screw holding capacity increases by 33%. Density oscillates around the value of 650 kg / m3, possible deviations occur through the influence of the anatomical structure of wood and glue joints.

Keywords: plywood; lignocellulosic composite; density profile; modulus of elasticity; bending strength

INTRODUCTION

According to standards, plywood is a lignocellulosic composite material made of glued intersecting thin layers of wood at right angles. The most commonly used types of wood for production are: pine, birch, alder, beech and exotic species. The number of layers of plywood is usually odd, connected with adhesives: UF (urea-formaldehyde), MF (melamine-formaldehyde), MUF (melamine-urea-formaldehyde), PF (phenol-formaldehyde). Due to the type of glue used, the plywood is dry and water-resistant. Plywood is widely used in construction, boatbuilding, aviation, transport, packaging production, home and office furniture, where, using the most common metal connectors, they perform many functions.

The most important factors affecting the strength of the plywood are: wood grade, wood density, cutting and veneer drying temperature, time, pressure and the type of glue used in process. By controlling their values, it is important to determine the optimal plywood production factors without losing the binding strength (Demirkir et al. 2013). Furthermore, efforts to move to more low energy, environmentally friendly building materials and minimize costs (Kruger and Laroca 2010; Bulcke et al. 2011) have also resulted in the search for new building materials and concepts that play an important role in these engineering products.

A very important factor determining the physical and mechanical properties is the wood grade used and the associated average density. Plywood made of coniferous species show higher mechanical values than those made of soft deciduous wood, as shown by Aydin et al. (2006) on the example of plywood spruce *(Picea orientalis* L.*)* and poplar *(Populus × eureamericana)*. Another factor that affects the strength of layered laminate materials is the moisture of used veneers for the production. As demonstrated by Aydin et al. (2006) the higher the humidity of veneers used in the production process, the mechanical strength of the plywood decreases. An important factor determining the strength of the plywood is the type of glue used during the production process. Studies have shown that the use of MUF adhesive positively influenced bending strength and modulus of elasticity in comparison to the use of UF adhesive (Aydin et al., 2006). Matan and Kyokong (2003) for solid wood came to similar conclusions. The flexural strength and modulus of elasticity are strongly influenced by the direction of bending: along or across the fibers of the external planes, the size of the samples: laboratory or large-size and the chosen test method, ie three-point or four-point bending (Karshenas and Feely 1996).

When using plywood and other lignocellulosic layered composites, the key is to choose the right connectors, the most commonly used are screws. Due to their availability in various lengths, diameters and high stiffness, screws are an effective tool for reinforcing wooden structures. During the screw withdrawal resistance (SWR), the diameter of the thread and the loading direction during the test were decisively influenced. In the direction perpendicular to the plane, higher results were achieved than in the direction parallel to the plane, i.e. the side of the plywood (Maleki et al 2017). The results of Ellingsbo and Malo (2012), Carradine et al. (2009) and Blass and Bejtka (2004) showed that the force of pulling the screws in a parallel or perpendicular position to the fibers depends on the size of the screw and the depth of screwing.

The aim of conducted research was to investigate the influence of the structure (including number of layers) of the lignocellulosic layered composites on the selected mechanical and physical properties of composite.

MATERIALS AND METHODS

Investigated material

The layered lignocellulosic materials, in the shape of plywood, of the 3, 5, 7, 9 and 11 layer number have been used in this research. The composites have been produced in the laboratory conditions with use industrially rotary cut 3.2 mm nominal thickness *Pinus sylvestris* L. veneers. The glue mass used to produce the composites, applied with amount of 180 g/m^2, was composed on industrial urea-formaldehyde resin Silekol S123, wheat flour as a filler and the water solution of ammonium sulphate as a hardener. The resin/hardener/filler/water total dry weight (if applied) ratios were as follow: 100/2/10/5. The specific unit pressure was 2 MPa, the pressing temperature was 140˚C, and the pressing time was calculated on the basis of Kollmann's equation (1). The produced composites after production have been conditioned in the air environment of 20˚C/65% relative humidity to constant weight prior to the further tests. The tests were carried out based on PN-79/D-97005 and PN-83/D-97005.11 standard.

$$T = 4\ \text{min} + \frac{1\,min}{mm}\, of\ thickness\ from\ the\ surface\ to\ the\ bonding\ line\ nearest\ the\ middle\ of composite\ thickness \quad (1)$$

Density profile

The density profile was tested on 15 plywood samples 3, 5, 7, 9 and 11 layers, 3 of each type. Samples measuring 50 x 50 mm (length x width) and thickness ranged from 8 to 30 mm. The density profile test was carried out on a density profile analyzer DA-X (GreCon), whose measurement method is based on X-rays. The measurement was carried out at a rate of 0.10 mm / s and a sampling rate of 0.02 mm.

Bending strength and modulus of elasticity

The test was carried out based on the PN-EN 310:1994 standard, on 42 plywood samples with dimensions of 300 x 50 mm (length x width, respectively), thickness from 8 to 30 mm. In addition, the samples were weighed, which made it possible to determine the density of each sample. The test was carried out on a universal testing machine.

Screw withdrawal resistance (SWR)

For testing the screw withdrawal resistance were used 102 samples having the dimensions 50 x 50 mm (length x width), the thickness ranged from 8 to 30 mm. The test was carried out in accordance with PN-EN 320: 2011 using the pull-push method.

RESULTS

Density

The density increases from 620 kg/m^3 of 3 layer plywood to about 665 kg/m^3 in 5 layer plywood (figure 1). Then it drops to the level of 655 kg/m^3 in the 9 and 11 layer plywood. Analysis of the average density values of the tested layered composites, taking into account the spread of results around the averages (standard deviation), showed that there are no statistically significant differences in the average values of plywood density. The linear regression coefficient at the level R^2 = 0.38 confirms this. The density results were in the range of 620 to 663 kg/m^3. The data indicate the density of pine plywood at the level of 550 to 620 kg/m^3 (Martitegui et al. 2008), and the site of the plywood manufacturer is given a density of approximately 610 kg/m^3 (https://www.sklejkaeko.pl/sklejka-sosnowa/). The difference may result from uneven application of glue, zones with increased density or a large proportion of late wood or heartwood.

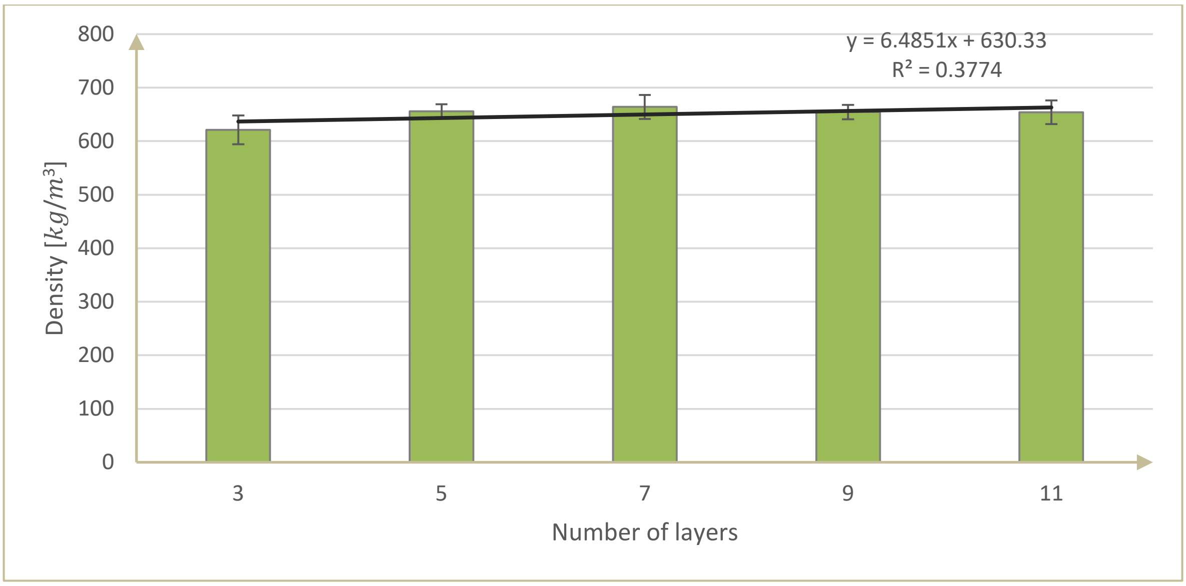

Figure 1. Density of tested layered lignocellulosic composites.

Density profile

The density profile graph (figure 2) shows lower density zones denoting wood and high density zones denoting glue joints. The density of wood is in the range of about 600 to 700 kg/m^3, deviations and variations in density are caused by the construction of wood, e.g. by knots occurring in veneers. The density of the adhesive joint varies from 1000 to 1100 kg/m^3 and the differences appearing are a consequence of uneven application of the adhesive to the veneer during the production process.

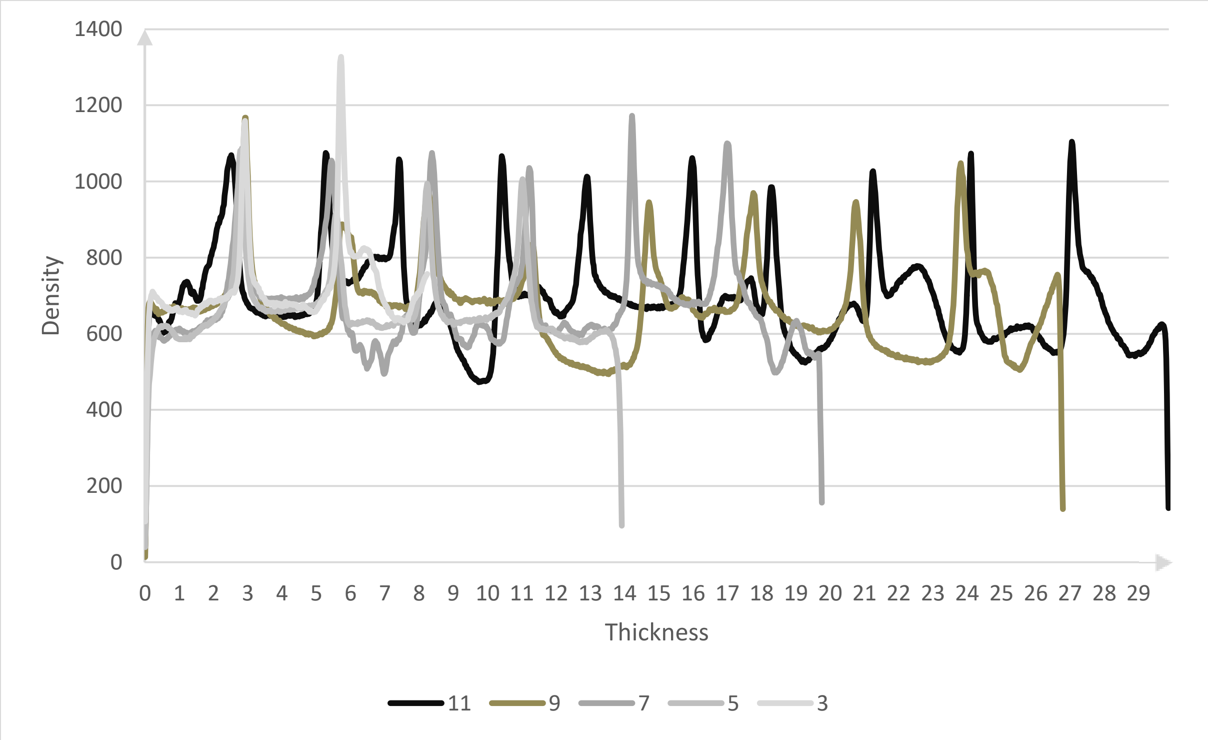

Figure 2. Density profiles of investigated plywood of different layer numbers.

Bending strength

The highest bending force (100 N/mm^2) was to be used for the thinnest plywood - as shown in figure 3. The 5-ply plywood was characterized by a strength of 65 N/mm^2, seven-layer about 50 N/mm^2. The nine-layer and eleven-layer boards have very similar values (40 N/mm^2) and the error bars have analogous values. Statistically significant mean differences can be seen in the case of the thinnest plywood (3) relative to the remaining through a large difference in results. Similarly, the situation of the composite layered results with respect to 9 and 11 layered composites, where the mean and values of standard deviations differ significantly. The graph shows the decreasing tendency of bending strength relative to the increase in the number of plywood layers. The linear regression coefficient (R^2 = 0.85) confirms this relationship. 3-ply plywood has reached 100 N/mm^2 and is a higher result than those given in the literature of 62 N/mm^2 for plywood made from spruce veneers (Aydin et al. 2006). The result for the 7-layered composite (51 N/mm^2) is comparable to literature data for 18mm plywood (56 N/mm^2) (Maleki et al. 2017).

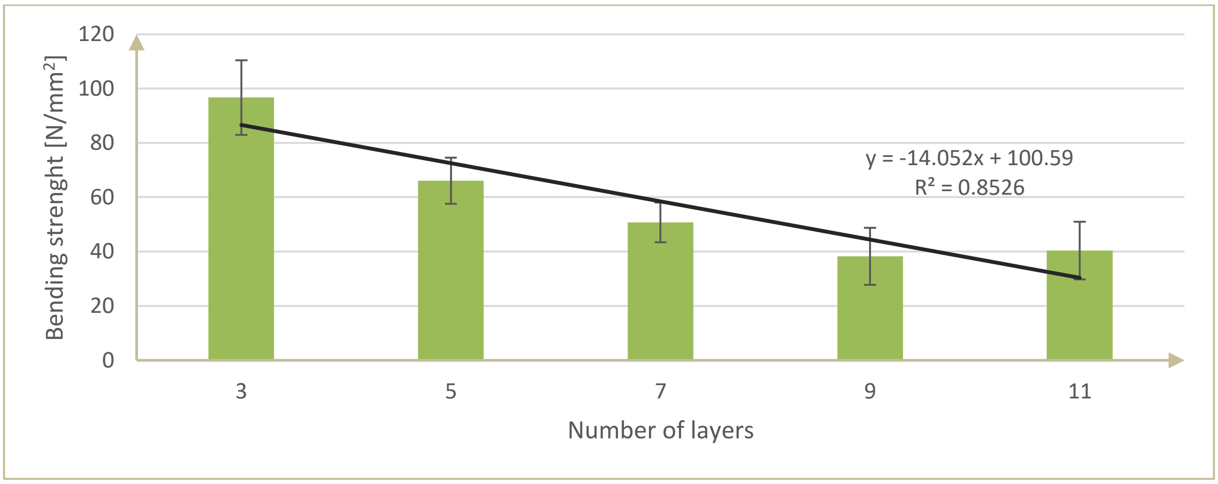

Figure 3. Bending strength of tested layered composites of different layer number.

Modulus of elasticity

The results of the MOE study (figure 4) show a downward trend. Plywood with the smallest number of layers was characterized by the largest modulus of elasticity at the level of 14 000 N/mm^2. The 9 and 11-ply plywood showed the lowest value of the elastic modulus at the level of about 4 000 N/mm^2. The graph shows the linear downward trend of MOE due to the increasing number of composite layers, and the linear regression coefficient (R^2 = 0.92) confirms this. Based on the preliminary analysis of the significance of the differences, it can be concluded that the averages differ significantly from each other, only the MOE results of the plywood 9 and 11 layer overlap. The results of the MOE composite layer 10130 N/mm^2 (thickness 14 mm) and 7 layered 5915 N/mm^2 (20mm) were lower than the literature data plywood 12mm, 12500 N/mm^2 and plywood 18mm, 8430 N/mm^2 (Nandanwar et al. 2012) by 19% and 30% respectively. Differences occurred due to different thickness of samples, but this is confirmed by the fact that MOE decreases with the thickness of the samples / number of layers. According to other data for a 7 ply plywood (5915 N/mm^2) a comparable result of 5700 N/mm^2 was obtained, the results were influenced by the density of the wood used, the poplar is less dense wood of about 100 kg/m^3 (Maleki et al. 2017).

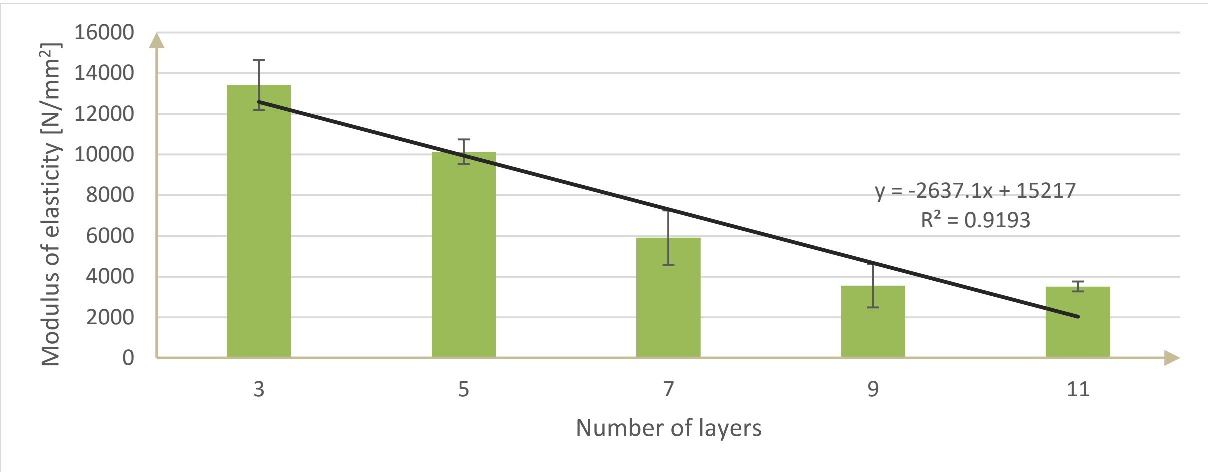

Figure 4. Modulus of elasticity of tested composites of different layer number.

Screw withdrawal resistance (SWR)

On figure 5 the resistance of screw withdrawal from the tested composites of different layer number has been presented. As in is shown, the lowest mean value of SWR, 124 N/mm, has been found in case of the composite of lowest tested number of layers (3), when the highest average value of SWR, over 159 N/mm, has been found for the composite of the highest number of layers (11). The difference between the highest and lowest average values of SWR is over 28% in regard to the lowest average value. It should be concluded that there is linear dependence between the SWR and number of layers of tested composites, where the SWR increases with the number of layers raise, and the high linear regression coefficient (R^2 = 0.93) value confirms this remark. When analysing the average values of SWR and the distribution of all single results around mean values, it can be pointed that there is statistically significant difference of mean values of SWR only when compare the values for 11 layers plywood and remaining tested composites. Obtained results for 5-layered plywood (132 N/mm) are lower than the literature data by 12%: 150 N/mm for southern pine (5 layers). The result of the 7-layered composite (132 N/mm) is 9% lower than the result of the Douglas-fir 7 layer (145 N/mm) (Erdil et al. 2002). Differences may result from the application of other standards for research, which is reflected in the shape of screws. According to other literature data, the results obtained for the 7-layer composite (132 N/mm) are higher compared to the result 109 N/mm for LVL 18 mm, the result for the 11-layer composite (159 N/mm) is higher than the 11-layer poplar plywood (92 N/mm) The result was influenced by the species of wood from which LVL and plywood were made (Maleki et al. 2017).

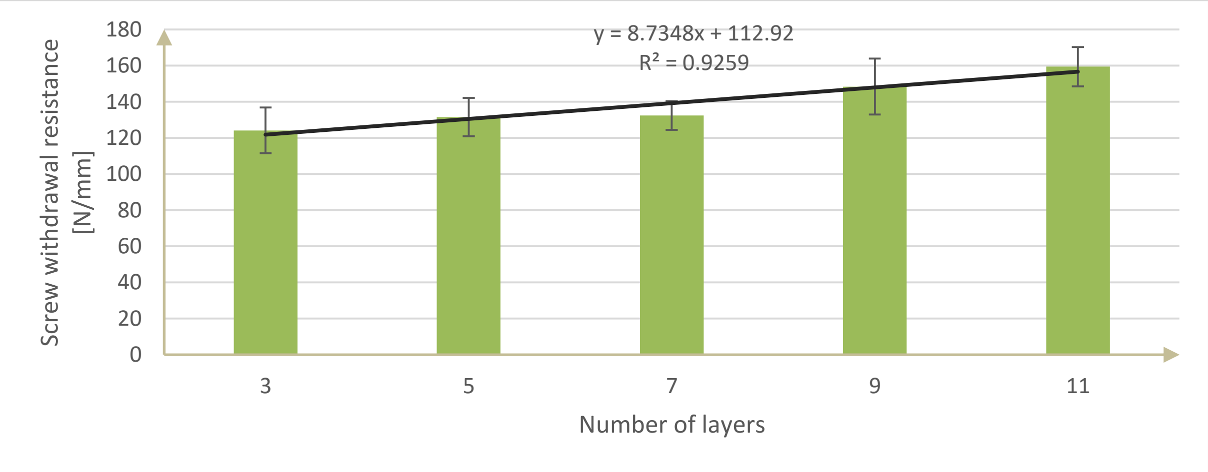

Figure 5. Screw withdrawal resistance of tested composites of different layer number.

CONCLUSIONS

The study confirmed the hypothesis about the influence of structure and thickness on selected properties of the layered lignocellulose composite. The value of MOE and bending strength decreases as the thickness of the plywood increases by 71% and 60%, respectively. Screw withdrawal resistance increases with 33% as the number of composite layers increases. The density of the plywood is maintained at the level of about 650 kg/m^3, density fluctuations, which are illustrated by means of the density profile, mean zones of layers of wood burdened with anatomical structure defects e.g. knots or cracks and areas of glue joints.

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Streszczenie: *Wpływ struktury na wybrane właściwości kompozytu lignocelulozowego.* W ramach badań określono wpływ ilości warstw i strukturą sklejki na wybrane właściwości fizykomechaniczne. W zakresie pracy wykonano badania: wytrzymałości na zginanie i modułu sprężystości, oporu przy osiowym wyciąganiu wkrętów oraz profilu gęstości. Potwierdzono wpływ wzrostu grubości na wybrane właściwości sklejki. Wytrzymałość na zginanie spada o 60%, moduł sprężystości o 71%. Wraz ze wzrostem liczby warstw kompozytu wzrasta zdolność utrzymywania wkrętów o 33%. Gęstość oscyluje wokół wartości 650 kg/m^3, możliwe odchylenia występują przez wpływ budowy anatomicznej drewna oraz spoin klejowych.

Corresponding author:

Grzegorz Kowaluk
Nowoursynowska Str. 159
02-787 Warszawa, Poland
email: grzegorz_kowaluk@sggw.pl
phone: +48 22 59 38 546

ORCID ID:

Kowaluk Grzegorz 0000-0003-1463-0540