Production of Layered Wood Composites with a Time-Saving Layer-By-Layer Addition

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Multilayered wood composites were manufactured by introducing a cyclic pressing manufacturing method in which plies were added subsequently between each cycle as an alternative to the conventional single-cycle method based on a continual pressing of an entire set of veneers. The goal of the proposed cyclic method was to reduce the pressing time of multilayer wood-based composites. Scots pine veneers with two different moisture contents (5% and 10%) were selected. Heat transfer dynamics showed that the heat transfer through the veneers was remarkably dependent on the moisture content of the veneers, so the pressing time of the veneers with higher moisture content can be easily reduced. The density profile showed that by adding layer by layer, the density of the core is higher than that of the external layers. However, the mechanical tests of the composites produced by cyclic-pressing showed that the bending strength and modulus of elasticity, as well as the internal bond of composites were similar and in some cases even higher than composites pressed in a conventional way, while having pressing time reduced to less than a half.

Keywords: Veneer; Composite; Pressing time; Wood; Moisture content; Modulus of rupture; Internal bond; Modulus of elasticity

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INTRODUCTION

Wood-based layered materials, such as plywood or laminated veneer lumber (LVL), are products with high and stable market demands. These materials have a high strength-to-weight ratio, and their properties are even over the entire surface (Deam *et al*. 2008). However, compared with other wood-based composites, prices of veneer-based products have been traditionally higher due to the industrial requirements, which demand flawless appearance and higher quality timber (Vlosky *et al*. 1994). Surface roughness, as well as a proper application of adhesives, has been demonstrated to play an important role in the final properties of plywood (Bekhta *et al*. 2009). A second important factor is production costs, which are strongly connected with the efficiency of the production line.

Although cost-effectiveness is crucial to determine the optimum factor for plywood manufacturing, avoiding any loss in bonding strength is also essential. The most important factors affecting the bonding strength of plywood are wood species, adhesive type, wood density, veneer peeling temperature, veneer drying temperature, and relative moisture content (Demirkir *et al.* 2013). Moreover, the production efficiency of plywood is limited

by pressing abilities, thus making pressing time another key factor for plywood industry (Hoong and Paridah 2013).

Innovations focused on reducing the pressing time, together with other priority factors, can be profitable for producers who want to increase the manufacturing capacity. Moreover, to reduce economic costs of production, some or several parameters should be reduced. A pressing time that is either too short or too long is not recommended, as a short pressing time may not be enough to transfer heat through the pressed materials to reach the core zone, having deficiencies in the curing of the resin, while a long pressing time can destroy a thermosetting resin, thus degrading the mechanical properties of the product. Similar remarks concerning the optimal pressing time of particleboards were found in binderless panels (Baskaran *et al.* 2015).

The time of pressing wood-based layered materials such as plywood is directly related to the thickness of the individual plies as well as the final thickness of the elaborated composite as well as to the density of the selected tree species (Bekhta *et al.* 2012). This phenomenon is common to other bio-based materials. It has been observed that pressing time also influences the properties of particleboards from different species (Ashori and Nourbakhsh 2008). However, pressing time does not have a linear connection with the mechanical or physical properties of experimental panels. One way to reduce plywood-pressing time is by incising the veneers prior to plywood composition. Previous studies have explored the effect of incising the veneers prior to manufacturing the composites, which resulted in a reduction in pressing time by 27% for 21 mm thick 7-ply plywood, and by 32% for 40 mm thick 13-ply laminated veneer lumber (Troughton and Lum 2000; Wang *et al*. 2003).

Considering the fact of veneers having low heat transfer, and that pressing time depends on the thickness of the pressed material, a suitable approach to increase the heat transfer through the pressed wood layers could be achieved by reducing the thickness of the pressed materials. In this sense, the aim of this research was to evaluate time gain as well as physical-mechanical properties of multilayered wood composites that were produced by adding successive layers (veneers) with different pressing times.

EXPERIMENTAL

Materials

Industrially produced Scots pine (*Pinus sylvestris* L.) veneers were supplied by STEICO Sp. z o. o., Poland. The nominal dimensions of the industrial rotary cut veneers were 1000 mm x 1000 mm x 3.20 mm, length x width x thickness, respectively. Industrial size veneers were cut into sheets of 330 mm x 330 mm. Twin sheets were prepared in such a way that each of the two sheets was cut along the fibers of the industrial size sheet. This approach was undertaken to minimize the influence of the variability of veneer properties as density, annual rings distribution, wood cross cut, *etc*. To measure the heat transfer dynamics through the veneers, 2 x 80 sheets (40 sheets with 5% MC and 40 sheets with 10% MC) were used. The remaining sheets were used to prepare the multilayered composites.

An industrially used phenol-formaldehyde resin was selected to produce the composites. The solid content of the resin was 50%, as measured according to Standard Methods (EN 827 2005). The gluing mass was prepared by mixing the selected resin with a water solution of $(NH_4)_2SO_4$ as a hardener, and wheat flour as filler, in a ratio of 100:2:10

based on the dry weight, resin: hardener solution: filler, respectively. The curing time of the above mentioned gluing mass in 100 ˚C was about 72 s, and the dynamic viscosity at 20 ˚C was about 180 mPa·s.

Methods

Veneer conditioning

After being cut, all veneers were oven dried to a constant weight at a temperature of 103 °C. Once dry, the first half of the sheets were stored in a climatic chamber to increase their moisture content (MC) to *ca.* 5% and the second half of the sheets were conditioned in a climatic chamber to achieve a moisture content of *ca.* 10%. The actual moisture content of every veneer was measured using an ultrasonic MC control device.

Heat transfer dynamics

To calculate the optimal conditions for the pressing time of the layered wood composites, it was necessary to have data related to the heat transfer through the veneers. The measurement of heat transfer dynamics through veneers was conducted using the above-mentioned sheets. Heat transfer dynamics were measured by putting a computer-controlled thermocouple between each set of twin veneers; the system was then placed between the hot press plates at a temperature of 140 ºC and a pressure of 1.5 MPa. The time needed by the inside thermocouple to reach 80 ºC, 100 ºC, and 120 ºC was recorded by the computer.

Pressing time calculations

There are different methods to calculate the pressing time (t_p; min) needed to elaborate multilayered composites, different pressing times were calculated according to proposed calculations available in bibliography as shown in Eqs. 1 to 4,

$$t_p = K_t\,(1+(\Sigma e)^2) \quad (1)$$

where K_t is a constant coefficient (3 for press plates at a temperature of about 140 °C), and Σe is the sum of thicknesses of all the veneers in cm (Kull 1954).

$$t_p = K \times n \times e + 1 \quad (2)$$

where K is an empirically estimated coefficient (0.67), n is the number of the sheets in the pressed set of veneers, and e is the thickness of the single veneer (Boruszewski 2013).

$$t_p = 4 + 0.1e \quad (3)$$

In Eq. 3, e is the depth of pressed material in cm when measuring from the surface to the bonding line located nearest the middle of the pressed composite thickness (Boruszewski 2013).

$$t_p = 1 + 0.5e \quad (4)$$

In Eq. 4, where e is the depth of pressed material in cm (Thoemen *et al.* 2010). Assuming that the average thickness of a single veneer is 0.3 cm, and being 16 veneers for each composite, the pressing time according to Eqs. 1, 2, 3, and 4 is 73 min, 34 min, 28 min, and 25 min, respectively.

Production of the composites

Two different processes were followed for the manufacturing of the composites, as shown in Fig. 1. For both methods, a ZUP-NYSA PH-1P125 hydraulic press was used, with a pressure of 7.2 MPa and the plate temperature being set at 140 ºC. The amount of the glue mass, which was manually spread onto a single bonding line, was 180 g/m^2. All veneers in either kind of composite were oriented along the fibers (laminated veneer lumber), so there was no crossing orientation as is typical for plywood.

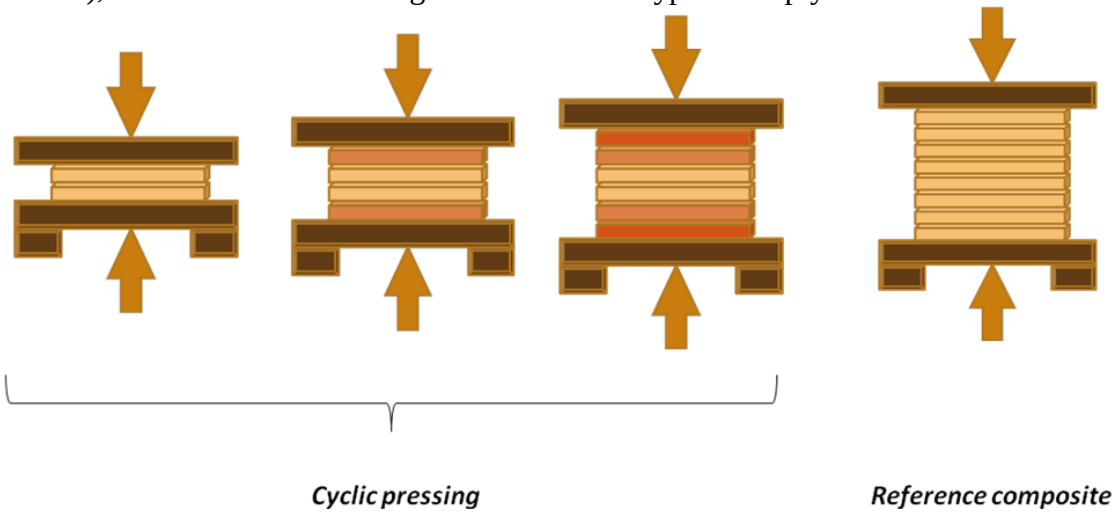

Fig. 1. Scheme of the two different manufacturing processes

The time of pressing composites under a single-cycle was established by use of Eqs. 1 to 4. The first manufacturing method consisted of a set of 16 veneers being pressed for 25 min. This method is considered as a reference, as the aforementioned calculated time is widely applied as a "best practice" in industry, elevating productivity. The second method consisted in the time-reducing cyclic pressing, for which pairs of veneers were added and pressed during 40 seconds in case of wet veneers and 60 seconds in case of veneers with 5% MC until 16 veneers were bonded together. This method is considered as cyclic. Table 1 synthesizes the processing parameters for all the elaborate composites.

Table 1. Sample processing parameters

Sample name	Veneer MC [%]	Method	# of veneers	# of cycles	Pressing time [min]	Temperature [ºC]	Pressure [MPa]
$R_{5\%}$	5	Reference	16	-	25	140	7.2
$C_{5\%}$	5	Cyclic	16	8	12	140	7.2
$R_{10\%}$	10	Reference	16	-	25	140	7.2
$C_{10\%}$	10	Cyclic	16	8	9	140	7.2

Core temperature of the composites during pressing

The initially adopted shortest pressing time, based on the previously established heat transfer dynamics, was 40 s for a single pair of veneers with 10% MC, and 25 min for reference material (a set of 16 veneers). To measure the core temperature of the pressed composites, a thermocouple connected to a computer was placed between the two veneers located in the middle of the composites.

Density profiles of the composites

To measure the density profile (DP), all the samples were cut into 50 mm x 50 mm x thickness test specimens and were analyzed in a Grecon DA-X measuring unit (Alfeld, Germany) with direct scanning X-ray densitometry across the panel thickness, with an incremental step of 0.02 mm.

Mechanical testing of the composites

The modulus of rupture (MOR) and modulus of elasticity (MOE) were determined according to EN 310 (1993). Internal bonding (IB) was determined according to EN 319 (1993). The tests of the mechanical properties were conducted on a laboratory-testing machine custom made by Research & Development Centre for Wood-Based Panels Sp. z o. o. in Czarna Woda, Poland. Twelve samples of each composite type per test were used, with the exception of DP, for which three samples were used.

Prior to the further tests, the produced composites were conditioned under 20 °C/65% temperature/relative moisture content, respectively, in climatic chamber custom made by Research & Development Centre for Wood-Based Panels Sp. z o. o. in Czarna Woda, Poland, to ensure the constant weight of the samples. For every test, samples were selected in the light of their similar density according to standard EN 323 (1993).

Statistical analysis

The data for each test were subject to variance analysis (ANOVA), and t-tests were used to determine statistical significance ($\alpha = 0.05$) of differences between factors and levels (IBM SPSS 20 software, Armonk, NY, USA). A comparison of the means was performed when the ANOVA indicated a significant difference, employing the Duncan test. The results on the plots represent the average value and ± standard deviation bars.

RESULTS AND DISCUSSION

Figure 2a shows the heat transfer dynamics through veneers with different moisture content by recording the temperature between two veneers being hot-pressed. The veneer overheating time varied considerably, depending on the moisture content. The average time to reach 80 °C, 100 °C, and 120 °C inside the veneers with 10% MC was approximately 24 s, 32 s, and 47 s, respectively.

To overheat the set of two veneers with 5% MC, it was necessary to use a longer time: 28 s to reach 80 °C, 42 s to 100 °C, and 72 s to 120 °C. This means that the time necessary to reach 100 °C between the two veneers with 5% MC was more than 31% longer than the overheating time under the same conditions for veneers with 10% MC. The dependence of the variation of the overheating time in the function of changing (increasing) humidity is shown in Fig. 2b. In the case of veneers with 5% MC heated to 100 °C, the scattering of individual results was relatively small. In the case of veneers with 10% MC, the tendency to shorten the veneer overheating time with an increase in veneer moisture content was noticeable, although the correlation was disputable ($R^2 = 0.41$).

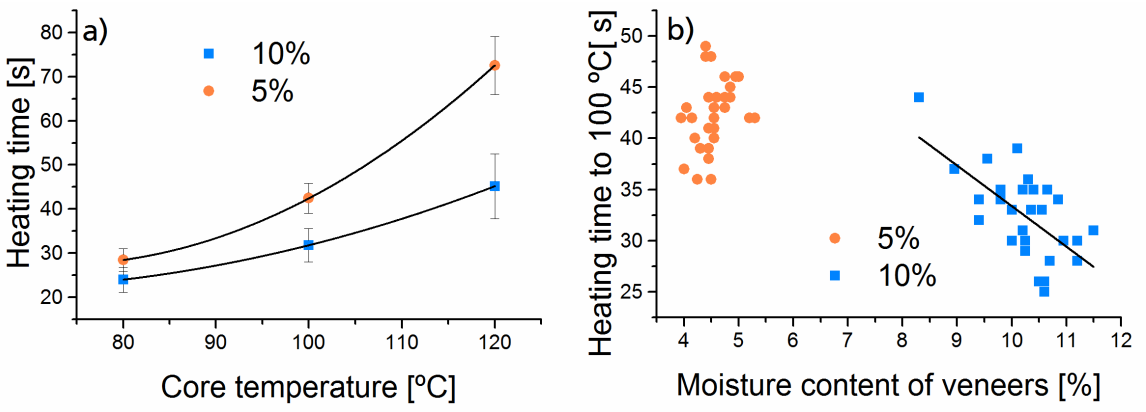

Fig. 2. a) Heat transfer dynamics through different kinds of veneers and b) differences between heat transfer through veneers of various moisture content

As shown in Fig. 3, the temperature of the core layers of the pressed set of veneers during the single-cycle increased almost linearly to a maximum temperature of 100 ºC throughout the entire pressing, the temperature at the surface of the press plate was kept at 140 °C. The temperature of the cyclically compressed material varied from *ca.* 86 °C to almost 120 °C during the period corresponding to the pressing cycles and the addition of subsequent veneer layers. It is worthy to point out that the curing of a urea-formaldehyde resin can be initiated at 75 °C (Chow and Steiner 1975) and has its best curing performance at 120 ºC (Lin and Lee 2018). Therefore, while the curing of the resin between the core layers could be started at the beginning of the composite fabrication, in case of single-cycle composites this temperature was reached after more than 600 s, time at which the cyclic pressing composite was already finished. However, even though the curing time of the applied glue mass at 100 °C was 72 s, it should be pointed that after 600 s the glue mass was fully cured even when heated to 75 °C.

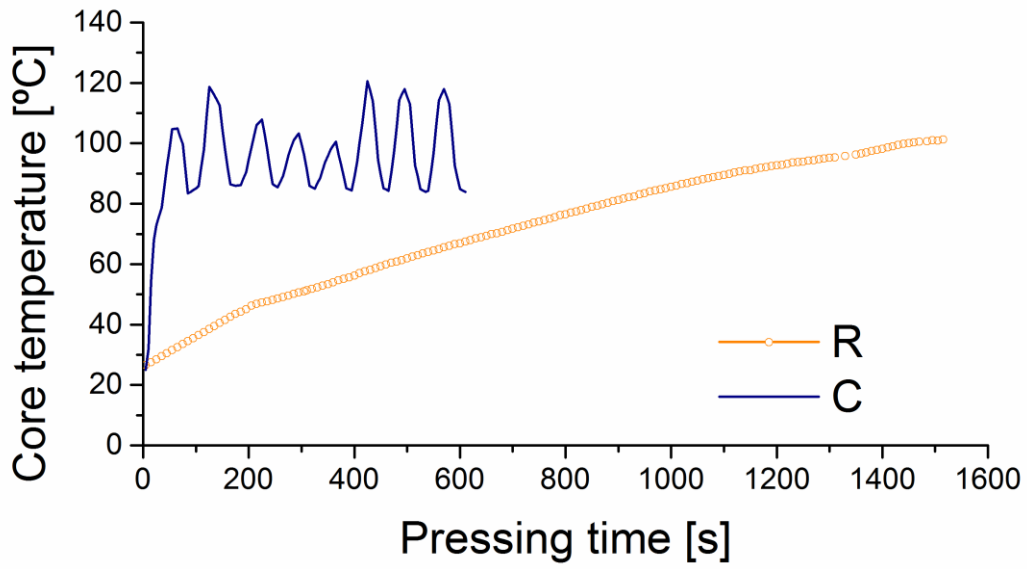

Fig. 3. The temperature in the composite core while pressing with a different approach

The vertical density profiles of two differently produced composites are presented in Fig. 4. Reference composites show similar density patterns between the different layers. There was no significant change in density profile in the middle layers of the reference composite, though the density of the veneers increased closer to the surface. This was more clearly evident in the 5% MC composites than in 10% MC ones. The reason for this is that the face layers were in contact with the hot shelves of the press for a longer time, thus the working heat transferred from shelves through the surface layers to the core of the pressed composite has much more influence for the face layers, which have been densified more. In case of composites from cyclic pressing, the veneers located in the middle of the composite had higher densities than those at the surface. This is related to the longer time of pressing for the core layers; an effect that is more appreciable in case of composites made of veneers with 10% MC, in which besides heat-transfer and densification, it has to be added the moisture evaporation, which delays the densification of the external layer.

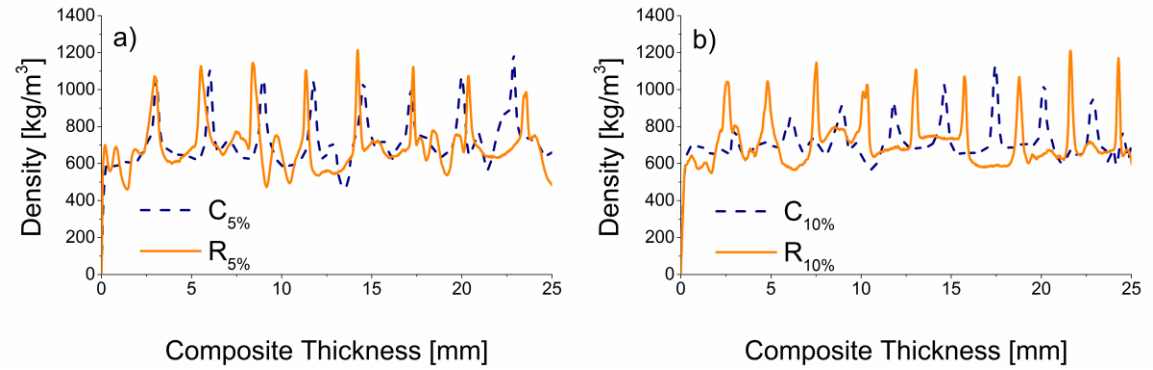

Fig. 4. Density profiles of a) 5% MC veneers and b) 10% MC veneers composites pressed under a different pressing time

Mechanical properties are shown in Fig. 5. The analysis of Modulus of Rupture (MOR) is presented in Fig. 5a. It can be appreciated that there was no statistically significant influence of the pressing technique (R or C) on the MOR of produced composites, as differences in MOR between composites made with veneers with 10% MC were ~2.2%. The statistically significant difference of MOR among all types of veneers and pressing regimes was found for those composite pressed in a cyclic process and composed from veneers with 5% MC. The increase in the MOR value of this composite compared with the lowest presented value ($R_{10\%}$) was over 27%. The reason for this effect may be the differences between the density profiles of the investigated materials, as shown in Fig. 4. While bending flat and straight samples, the highest tension and compression strains occur mostly in the face layers of the tested sample, whereas the shear stresses take place in the core layer. Because solid wood strength is the highest during tension along the fibers, the damage to the sample can occur due to reaching the limit of the stress not on the tensioned side of the sample. In addition, the compressive strength of wood is higher than shear strength. Thus, the damage to the wood-layered composite, which determines the MOR value, quite often happens due to the shear break in the core layers. To avoid this, the densification of the core layers of the composite is necessary. This effect can be reached when the layered composite is pressed cyclically, with the core layers being more densified compared with the face layers. This explanation is supported by the pictures of samples damaged during IB testing (Fig. 6). The samples with the highest MOR ($C_{5\%}$) during IB test were broken far from the middle of the thickness (Fig. 8c), whereas the samples with

the lowest MOR ($C_{10\%}$) were broken during the IB test almost in the middle of the thickness (Fig. 8b).

The results for the modulus of elasticity (MOE) are presented in Fig. 5b. Although there was no statistically significant difference between the MOE values for the tested composites, the highest MOE was that of $C_{5\%}$, whilst the lowest MOE corresponded to $C_{10\%}$. This sample had also the highest standard deviation, meaning that in case of MOE, the wet composites had an uneven elasticity, which may be related to the drying speed, related to a sudden rigidity achieved at fast dryings. The internal bond strength of the different composites is shown in Fig. 5c. The statistically significant difference of the mean value of IB (0.17 N/mm^2) was found for $C_{10\%}$, compared with the remaining results. This was the lowest value of IB recorded during the investigation. The highest IB – 0.75 N/mm^2 – was noted for $C_{5\%}$. The difference between the highest and lowest IB mean values was over 340%. IB for $R_{10\%}$ and $R_{5\%}$ was 0.60 and 0.61 N/mm^2, respectively which are similar, but with $R_{5\%}$ having a standard error of ~30%.

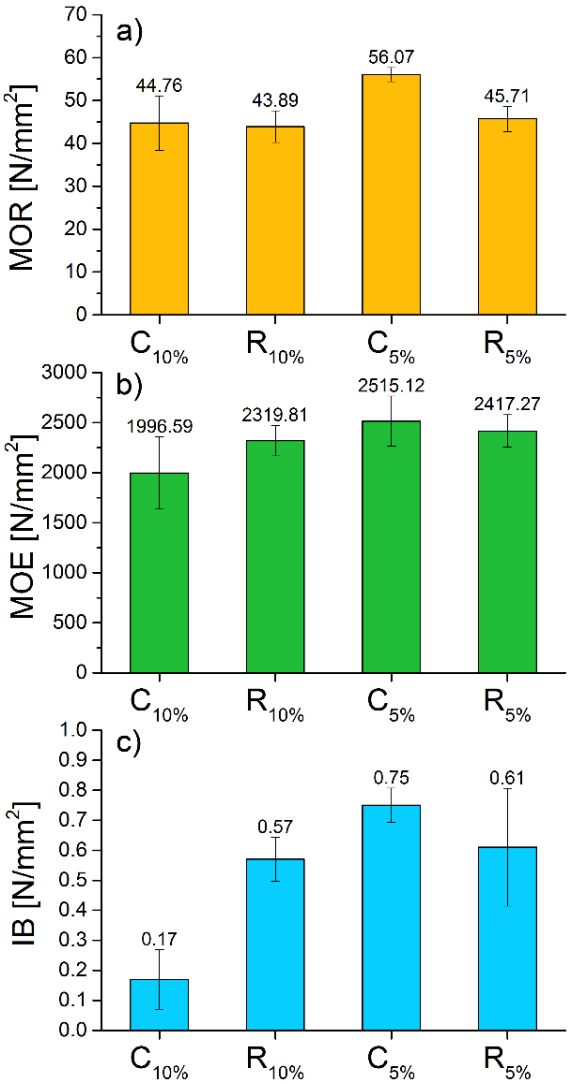

Fig. 5. Mechanical properties of the manufactured composites: a) Modulus of rupture; b) Modulus of elasticity and c) Internal bond strength

The damage to the samples after IB strength tests can be observed in Fig. 6. The destruction of the sample occurred at the bonding line between the veneers located near the surface. Thus, the pressing time was not enough to cure the resin; to avoid this destruction and increase the IB strength, the pressing time of the last cycle should be extended. The sample presented in Fig. 6b corresponds to $R_{10\%}$. The destruction of the sample in the middle of the thickness can be explained by the lowest densification of veneers being in this zone (Fig. 4), as well as the temperature of this zone increasing very slowly, because the heat was transferred through the entire set of veneers. The sample presented in Fig. 6c corresponds to $C_{5\%}$, the damage of the sample was found not in the middle of the thickness, but also far away from the sample surface. This means that the densification of the core layers was present, but also that the time of pressing of subsequent layers (60 s) was long enough, to prevent the destruction near the surface of the sample. The picture presented in Fig. 6d is the sample $R_{5\%}$; the break occurred in a similar location as was found for the previously described sample ($C_{5\%}$).

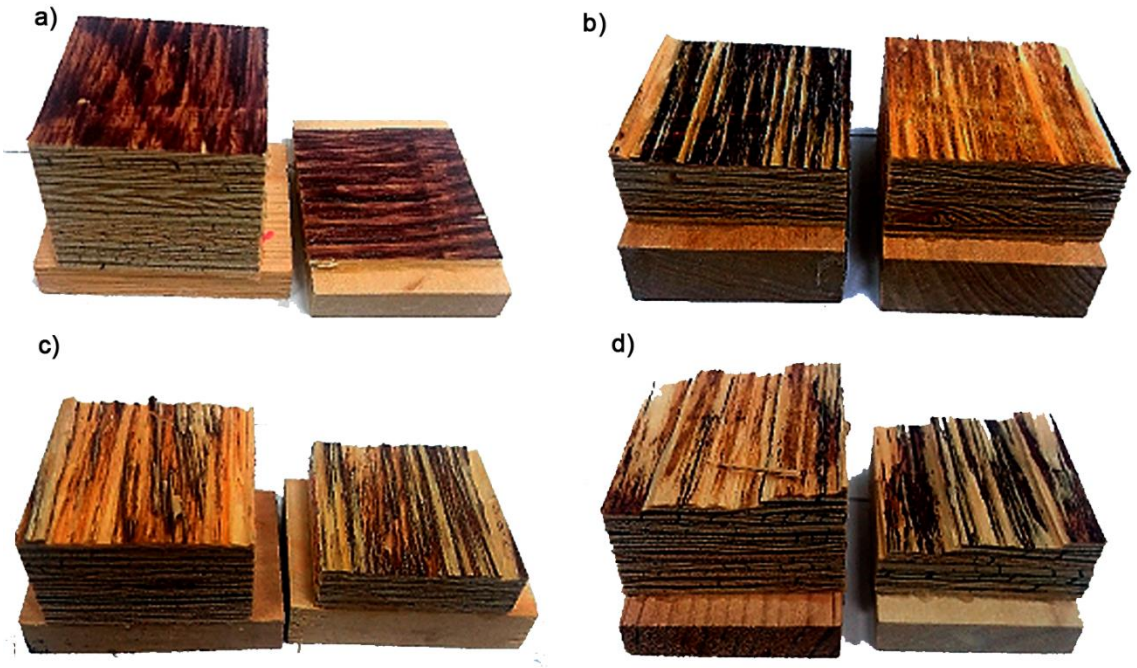

Fig. 6. Different forms of damage of samples after IB strength test: a) C10%, b) R10%, c) C5%, and d) R5%.

CONCLUSIONS

1. The achieved results show that in the case of veneers with 5% MC, it is possible to produce multilayered wood-based composites significantly reducing the pressing time up to a half of the conventional time when using cyclic pressing.
2. The selected pressing method was the main factor influencing the studied properties of the elaborated composites.
3. Mechanical properties of the composites produced by cyclic pressing (C), such as modulus of rupture, modulus of elasticity and internal bond strength, are equal or

higher compared to composites produced from the same materials under conventional pressing parameters (R).

4. The density profiles of the composites are different depending on the pressing technique. There can be an appreciable relation between the density profile of the composites and specific mechanical properties as internal bonding.

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REFERENCES CITED

Ashori, A., and Nourbakhsh, A. (2008). "Effect of press cycle time and resin content on physical and mechanical properties of particleboard panels made from the underutilized low-quality raw materials," *Industrial Crops and Products* 28(2), 225-230. DOI: 10.1016/J.INDCROP.2008.02.015

Baskaran, M., Hashim, R., Sulaiman, O., Hiziroglu, S., Sato, M., and Sugimoto, T. (2015). "Optimization of press temperature and time for binderless particleboard manufactured from oil palm trunk biomass at different thickness levels," *Materials Today Communications*, Elsevier, 3, 87-95. DOI: 10.1016/J.MTCOMM.2015.04.005

Bekhta, P., Hiziroglu, S., and Shepelyuk, O. (2009). "Properties of plywood manufactured from compressed veneer as building material," *Materials & Design* 30(4), 947-953. DOI: 10.1016/J.MATDES.2008.07.001

Bekhta, P., Niemz, P., and Sedliacik, J. (2012). "Effect of pre-pressing of veneer on the glueability and properties of veneer-based products," *European Journal of Wood and Wood Products*, 70(1–3), 99-106. DOI: 10.1007/s00107-010-0486-y

Boruszewski, P. (2013). *Przewodnik do Ćwiczeń z Podstaw Technologii Tworzyw Drzewnych*, Wydawnictwo SGGW, Warsaw.

Chow, S., and Steiner, P. R. (1975). "Catalytic, exothermic reactions of urea-formaldehyde resin," *Holzforschung*, Walter de Gruyter, Berlin / New York, 29(1), 4-10. DOI: 10.1515/hfsg.1975.29.1.4

Deam, B. L., Fragiacomo, M., and Buchanan, A. H. (2008). "Connections for composite concrete slab and LVL flooring systems," *Materials and Structures*, 41(3), 495-507. DOI: 10.1617/s11527-007-9261-x

Demirkir, C., Özsahin, Ş., Aydin, I., and Colakoglu, G. (2013). "Optimization of some panel manufacturing parameters for the best bonding strength of plywood," *International Journal of Adhesion and Adhesives* 46, 14-20. DOI: 10.1016/J.IJADHADH.2013.05.007

EN 310 (1993). "Wood-based panels. Determination of modulus of elasticity in bending and of bending strength," European Committee for Standardization, Brussels.

EN 319 (1993)." Particleboards and fibreboards: Determination of tensile strength perpendicular to the plane of the board," European Committee for Standardization, Brussels.

EN 323 (1993). "Wood-based panels: Determination of density," European Committee for Standardization, Brussels.

EN 827 (2005). "Adhesives: Determination of conventional solids content and constant mass solids content," European Committee for Standardization, Brussels.

Hoong, Y. B., and Paridah, M. T. (2013). "Development a new method for pilot scale production of high grade oil palm plywood: Effect of hot-pressing time," *Materials & Design* 45, 142-147. DOI: 10.1016/J.MATDES.2012.08.054

Kull, W. (1954). "Die Erwärmung von parallelflächigen Stoffen zwischen Heizplatten und die Bestimmung der Heizzeit bei der Holzverleimung, insbesondere bei der Spanplattenherstellung," *Holz als Roh- und Werkstoff* 12(11), 413-418. DOI: 10.1007/BF02628760

Lin, W.-S., and Lee, W.-J. (2018). "Influence of curing temperature on the bonding strength of heat-treated plywood made with melamine-urea-formaldehyde and phenol–formaldehyde resins," *European Journal of Wood and Wood Products* 76(1), 297-303. DOI: 10.1007/s00107-016-1154-7

Thoemen, H., Irle, M., and Sernek, M. (2010). *Wood-based Panels - An Introduction for Specialists*, Brunel University Press, London.

Troughton, G., and Lum, C. (2000). "Pilot plant evaluation of steam-injection pressing for LVL and plywood products," *Forest Products Journal* 50(1).

Vlosky, R. P., Smith, P. M., Blankenhorn, P. R., and Haas, M. P. (1994). "Laminated veneer lumber: A United States market overview," *Wood and Fiber Science* 26(4), 456-466.

Wang, B., Dai, C., and Troughton, G. (2003). "Development of a new incising technology for plywood/LVL production. Part 2. Effect of incising on LVL strength properties," *Forest Products Journal* 53(11–12).

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