Mechanical and Physical Properties of Boards Made from Recycled Paper

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Due to the increasing accumulation of wastes around the world, the demand for sustainable products is increasing. Paper is a commonly disposed of material that can pose problems even when it is recycled. The concept of using cardboard (CB) as a material for furniture production has been around for many years, but CB furniture does not last long. This study examined the feasibility of using post-consumer recycled paper to produce paper-based boards for furniture design. Cardboard (CB) and office paper (OP) were the main post-consumer materials that were used. The CB and OP were mixed with polylactic acid (PLA) and limestone. The boards were made at a temperature of 200 °C and pressed at a pressure of 3.5 N/mm^2 using a single opening hydraulic press. The physical and mechanical properties were tested according to the European standards for wood-based panels. Tests that are critical for furniture parts, such as the modulus of rupture (MOR), the modulus of elasticity (MOE), the internal bond, the screw withdrawal resistance, the thickness swelling, and the water absorption were examined. The paperboard samples exceeded some of the requirements for the general use of boards for interior fitments (including furniture) for use in dry conditions (Type P2) and for non-load bearing boards for use in humid conditions (Type P3).

Keywords: Wastepaper; Waste Cardboard; Composite; Bioplastic; Limestone powder; Post-consumer

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INTRODUCTION

In the last several years, the demand for environmentally friendly products has increased. The furniture manufacturing process produces a lot of waste material due to the volume of production and customized furniture design. During the design process, it is important to utilize the material efficiently to minimize waste. Approximately 5% to 20% of wood material is lost during the manufacturing process, which is a hinderance to a sustainable manufacturing process (Koo *et al.* 2017).

The goal of this study was to investigate the use of paper as a raw material to manufacture paper-based boards. The idea was to reuse post-consumer recycled paper for boards, which could be used for furniture in similar way as other wood-based products such as particleboards or Medium Density Fiber boards (MDF). Testing of its physical and mechanical properties was done according to the most important properties, corresponding to the tests used for wood-based products.

Previous research has been done with recycled pulps such as deinked pulp (DIP) and old corrugated container (OCC) with starch and urea formaldehyde glue (Sobotková *et al.* 2019). The paperboards were manufactured at different temperatures. These previous studies aimed to manufacture paperboard, test the mechanical and physical properties, and to assess whether they could replace wood products. When the testing of physical and mechanical properties was done, the authors of the previous research were looking for another option of paperboards without any glue. There was an idea of using plastic granulate in combination with paper in a similar way as are the industrially produced wood plastic composite (WPC) boards. Further investigation brought an idea of using PLA granulate to be able to prepare eco-friendly composite boards for furniture design use. According to Haider *et al*. (2018), PLA is a biodegradable material, although it needs special composting conditions. The research continued with the use of OP and CB with a biopolymer, polylactic acid (PLA).

Recycled paper is suitable material that can be used instead of wood to produce fiberboard panels. In recent years, the consumption and recycling of paper has become a focal environmental issue. Recycled paper is usually used as a raw material in the paper and pulp industry, although using wastepaper in the manufacturing of paper products can cause various problems. During the processing of recycled wastepaper, it is necessary to get rid of the printing inks and other additives on the material. This deinking process can reduce the strength of the fibers and negatively impact the environment (Dukarska *et. al*. 2018). Even though a lot of paper can be recycled, there is still a large amount of unused wastepaper (Dukarska *et. al*. 2018). Paperboard materials are frequently used as a packaging material for folding boxes and plates. For example, an inferior quality paperboard waste is also used to produce molded fiber packaging materials, such as egg trays (Groche and Huttel 2016).

The main component of paper is wood pulp. A paper sheet is formed over a mesh-like screen, where the pulp fibers are dispersed in water at a very low solids consistency. The plies within multilayer paperboard are usually bonded by adhesives, such as starch. The properties of a paper sheet can be modified to meet different requirements by using various fibers at different composition rates to change the density, porosity, or other structural properties (Xia 2002). Paper is based on cellulose fibers, which are derived from plants – mainly wood. Fiber for manufacture of paper can be also derived from wastepaper from which is made recycled paper (Kirwan 2013).

Paper has been used as a material in furniture design for many years. Examples of cardboard (CB) furniture pieces date back to 1969 with the famous designer Frank Gehry and his iconic Wiggle design chair (Kolesár 2009). Using CB as a material to produce furniture is sustainable and inexpensive, as it uses up to 99% less water, up to 50% less energy, and produces up to 90% less waste compared to using timber (Dovramadjiev *et al.* 2014).

Several studies have investigated the re-use of bio-based materials in the wood-based product industry. Various ligneous materials, such as banana stems, rice straw, bamboo, bagasse, cereal straw, coconut husks, flax, and hemp shives have been used for bio-composites in furniture design applications. The physical and mechanical properties of such materials are suitable to produce wood-based panels (Surip *et al.* 2012). The use of ligneous waste materials has other benefits. Egypt generates 30 million tons of agricultural waste per year, which can be used to produce paperboard material (Elbasiouny *et al.* 2020). By recycling agricultural waste, less carbon dioxide is emitted, as these materials are utilized rather than burned. In addition, medium-density fiberboard (MDF) and particleboard made from straw and bagasse tend to have stronger properties, such as internal bond strength, resistance to rupture, moisture resistance, and screw holding strength, compared to wood-based boards. The particleboards made from agricultural waste are non-harmful to health of the users because formaldehyde-based resins are not used in their production (Shehata 2016).

Incorporating recycled and waste materials into the manufacturing process can improve the environmental impact of the products. Figure 1 shows the eco-design strategy wheel of the product life cycle. The eco-design strategy wheel can provide a roadmap for the creation of composite materials from recycled paper materials (Costa and Gouvinhas 2003). Sustainably produced materials should be made according to the principles of a circular economy. These principles are outlined in the Action Plan of the European Union (EU circular economy action plan 2019). A circular economy is a system that aims to recycle products and materials in order to reduce waste. Utilizing waste materials can be a challenge for furniture designers. However, many designers have started to use eco-design strategies and circular economy principles to design furniture. For example, Bentu Design's Wreck tables are made of ceramic waste and Christophe Machet's modern collection of chairs are made of used polyvinyl chloride (PVC) pipes (Ladd 2018). Our research can be also considered as sustainable and circular. The manufactured boards are created from waste material, which is one of the rules of circular economy and they can also be upcycled again. Paper-PLA boards can be broken down into smaller pieces and milled by high-speed milling machines again. This process is like the way of recycling of particleboard, which can be recycled, and new boards can be created like in case of the leading manufacturers of particleboards.

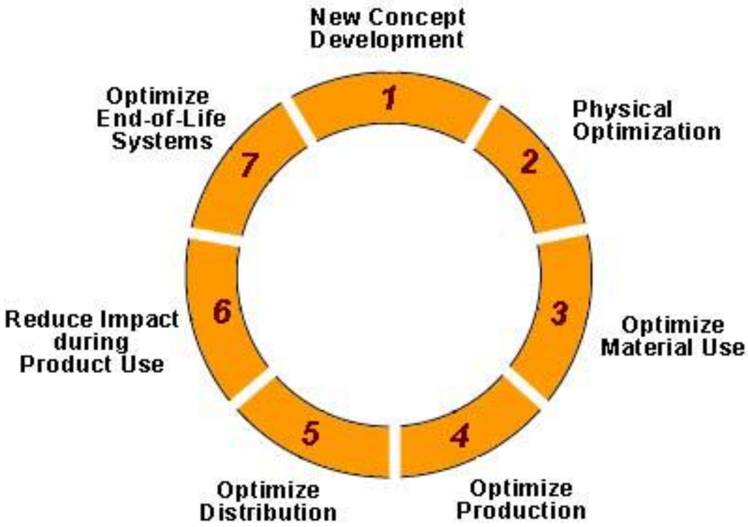

Fig. 1. The eco-design strategy wheel

EXPERIMENTAL

Materials

The two types of recycled post-consumer paper used in this study were cardboard (CB) and office paper (OP). Cardboard material is 100% recycled material, made of recycled paper fibers and textiles without chemicals added, since there is mostly no need of removing inks and colors. On the other hand, office paper must be bleached and deinked, to have typical white color. This process is lowering the physical properties of paper and that is why cardboard has better physical and mechanical properties (Dukarska *et al.* 2018).

The CB and OP were collected from several waste centers in Brno, Czech Republic. The CB and the OP were refined by a high-speed milling machine (FF Servis, Moravský Beroun, Czech Republic). The refining work was performed by FF Servis, Ltd. (Moravský Beroun, Czech Republic). The refining was carried out at specific refining conditions with the temperature of 23 °C with relative humidity of 50%.

Polylactic acid was used as the bonding material for the boards. Polylactic acid is a biodegradable plastic based on corn starch, wheat, sugar beets, or agricultural waste. Three-dimensional (3D) printing commonly utilizes PLA as a filament, and PLA is also widely used in biomedicine. The biodegradability of PLA in special composting conditions make it more attractive than other plastic materials (Panaitescu *et al.* 2017).

Another additive that was used was limestone powder. Its purpose was to make the surface of the boards harder and more resistant. In the wood-based product industry, limestone powder is typically added into the boards such as particleboards or MDF boards to give it higher resistance towards water and strength. According to Khorami and Ganjian (2013), when using waste cardboard together with limestone powder to produce fiber cement boards, the flexural strength of cement composite board can be improved by adding 10% limestone powder.

Fig. 2. The pre-formed CB before pressing

Methods

The paper-PLA boards were manufactured by pressing at a high temperature (200 °C). Four board samples were made from the CB and the OP. Each sample was composed of 2 kg of paper, 2 kg of PLA, and 1 kg of limestone. The boards were manually pre-formed in a wooden frame to dimensions of 600 mm × 600 mm × 18 mm. After the pre-forming process, the boards were pressed by hydraulic press (Strozatech s.r.o., Brno-střed, Czech Republic) with 3.5 N/mm^2 of pressure at 200 °C for 15 min. After the pressing, the boards were stacked vertically to cool them. The boards were conditioned at a 65% relative humidity and a temperature of 20 °C.

The testing samples were cut according to the dimensions in the European standard EN 326-1 (1998). The thickness swelling and water absorption after 2 h and 24 h of immersion in water (EN 317 1993), the modulus of rupture (MOR) and the modulus of elasticity (MOE) (EN 310 1993), the internal bonding (EN 319 1993), and the screw withdrawal resistance (EN 320 2011) were all tested. The samples were conditioned at a relative humidity of 65% and a temperature of 20 °C before they were tested.

The thickness swelling and the water absorption were tested on a ZH050/TH 3A universal testing machine (Zwick Roell AG, Ulm, Germany) according to the EN standard 317 (1993). Twenty samples were tested for each testing method. The MOE and the MOR of 10 samples were cut into 410 mm × 50 mm × 18 mm samples and measured on the universal testing machine, according to the EN standard 310 (1993).

Twenty samples with dimensions of 50 mm × 50 mm were cut for the internal bond test and the screw withdrawal resistance test, which were done according to the EN standards 319 (1993) and 320 (2011), respectively, using a universal testing machine. All the data were compared *via* a one-way analysis of variance (ANOVA) test, a Tukey honestly significant difference (HSD) test, and a regression analysis with the Statistica software (TIBCO Software, Palo Alto, CA).

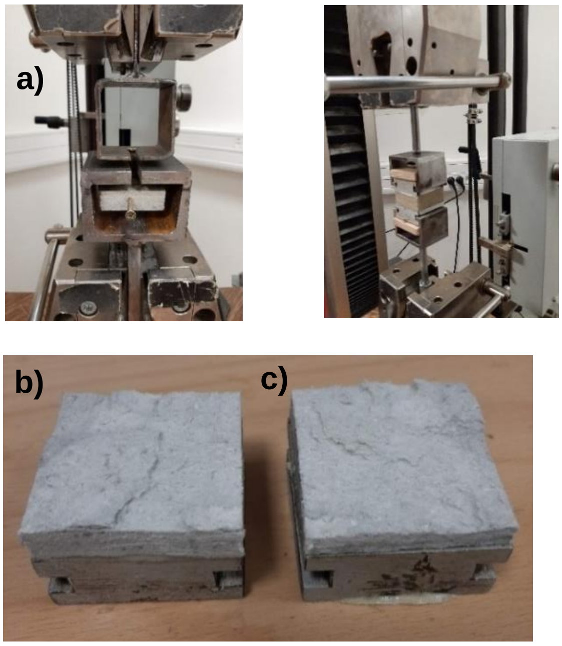

Fig. 3. The a) testing of screw withdrawal resistance and the internal bond strength; the b) CB-PLA and c) OP-PLA samples

RESULTS AND DISCUSSION

The testing of physical and mechanical properties was done according to the practices established for industrially manufactured boards and the usual properties that are tested. The testing regimen was derived from the tests done by one of the biggest suppliers of MDF boards, based on the panel products that were most comparable with the paper-PLA boards. The properties tested were: Density EN 323, Internal bond EN 319, Bending strength EN 310, Bending modulus of elasticity EN 310, and Thickness swelling 24 h EN 317. These are the most crucial properties for the boards used in furniture design.

Physical Properties

The results for the density, thickness swelling, and water absorption tests can be seen in Tables 1 and 2. Density of the boards allows the producer to predict how heavy the material will be for furniture use. The density of the CB was between 632.2 and 837.8 kg/m^3, while the OP had a density that ranged from 655.7 to 873.1 kg/m^3. The density of the paper-PLA boards can be compared with particleboards, because of similar manufacturing process and its properties. It is comparable with the two types of particleboards used in different conditions according to EN 312 (2010) “Particleboards: Specifications”. The particleboards are divided in the types of boards such as Type P2, P3, P5, P6. The paper-PLA boards are comparable with the Type P2 - Boards for interior fitments (including furniture) and Type P3 - Non-load bearing boards for use in humid conditions. The CB and OP materials had average values of 749.0 and 779.3 kg/m^3, respectively. The OP board had higher variance of the values in case of the density. The higher variance of OP boards is caused by variations in the milling times of the material. Due to the mechanical properties of office paper, which has weaker fibers than cardboard, this material did not require more milling, in contrast to the case of CB, which was milled four times. However, this caused the PLA not to spread in between the paper as uniformly as in case of CB, which was possible to see in the cross sectional cut in the testing samples.

Table 1. Density, Thickness Swelling, and Water Absorption Values of the CB

CB								
Testing Method	Mean	Geometric Mean	Minimum	Maximum	R	Median	Variance	Standard Deviation
Density (kg/m^3)	749.00	746.86	632.25	837.75	205.49	749.00	3134.98	55.99
Thickness Swelling 2 h (%)	1.74	1.47	0.43	4.44	4.01	1.67	0.99	0.99
Thickness Swelling 24 h (%)	3.73	3.61	1.78	5.96	4.18	3.75	0.81	0.90
Water Absorption 2 h (%)	6.05	5.79	4.18	12.16	7.98	5.34	4.06	2.02
Water Absorption 24 h (%)	15.97	15.67	11.13	22.71	11.58	15.63	9.90	3.15

Table 2. Density, Thickness Swelling, and Water Absorption Values of the OP

OP								
Testing Method	Mean	Geometric Mean	Minimum	Maximum	R	Median	Variance	Standard Deviation
Density (kg/m^3)	779.34	781.89	655.74	874.69	218.95	776.73	3214.94	56.70
Thickness Swelling 2 h (%)	6.10	5.95	3.54	9.73	6.18	5.50	2.82	1.68
Thickness Swelling 24 h (%)	7.64	7.47	5.11	10.61	5.50	7.70	2.14	1.46
Water Absorption 2 h (%)	49.07	47.44	27.54	73.72	46.18	49.61	171.59	13.10
Water Absorption 24 h (%)	64.94	63.30	47.35	82.41	35.06	64.48	101.30	10.06

Other important physical properties of industrially manufactured boards such as particleboards or MDF boards are thickness swelling and water absorption. It is important to know how resistant the material is towards water during the use in interior when the water or other liquids would be spilled over the table. The thickness swelling of the CB was between 0.43% and 4.44% after 2 h of immersion in the water and 1.78% to 5.96% after 24 h of immersion in the water. The thickness swelling of the OP was between 3.54% and 9.73% after 2 h of immersion in the water and 5.11% to 10.61% after 24 h of immersion in the water. The CB and OP materials had average thickness swelling values of 3.73% and 7.64%, respectively. According to the EN standard 312 (2010), the thickness swelling limit for Type P3 boards is 13%. The enhanced water uptake resistance was caused by adding plastic components. The particle size and number of high-speed milling cycles can also affect the thickness swelling. The OP material was subjected to two milling cycles, while the CB material was subjected to four milling cycles. Both board materials had very good swelling thickness results compared to the general requirements.

A one-way factor ANOVA was used to analyze the thickness swelling in the

CB and OP samples. The CB had a significantly lower thickness swelling value than the OP material, as can be seen in Fig. 4. The reason is probably higher density of the cardboard boards and bigger strength of CB fibers, which has led to stronger boards.

Water absorption resulted in a higher difference between CB and OP. Water absorption, which was 15.97% in case of CB and 64.94% in case of OP. The reason is again the nature of CB material, which is in general much stronger and resistant then regular OP material, which is weakened by bleaching, deinking process, and other additives.

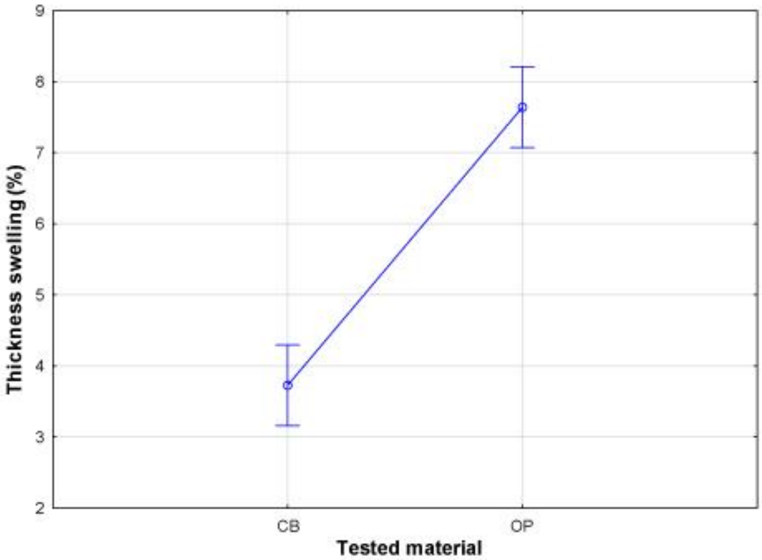

Fig. 4. The one-way factor ANOVA for the thickness swelling of the CB and OP materials after 24 h

Mechanical Properties

Flexural properties are crucial for board materials that are used for furniture, such as desk-tops and table-tops. Resistance to bending is needed so that the material will not be displaced when heavy objects are placed on the surface. That is why it was necessary to test bending strength according to standard EN 310 (1993) (Wood based panels. Determination of modulus of elasticity in bending and bending strength). The MOR of the CB ranged from 5.02 to 10.82 N/mm^2, with an average value of 8.45 N/mm^2. The MOR of the OP ranged from 1.98 to 6.57 N/mm^2, with an average value of 4.91 N/mm^2. The results were compared with the standard EN 312 (2010), where each group of boards and its use is described. CB boards can be compared with the requirements for boards for interior fitments (including furniture) (Type P2), where the value of MOR for boards with thickness between 13 to 20 mm is 11 N/mm^2 and MOE (Modulus of elasticity in bending) has the value of 1600 N/mm^2. In the present case the maximum value was 10.8 N/mm^2 of MOR the MOE of the CB ranged from 1215.0 to 2231.5 N/mm^2, with an average value of 1931.3 N/mm^2. The OP boards can be compared with the requirements for general purpose boards for use in dry conditions (Type P1), where the MOR is 10 N/mm^2. The MOE of the OP ranged from 582.9 N/mm^2 to 1992.5 N/mm^2, with an average value of 1529.2 N/mm^2. The higher MOE of CB, which was 1931.3 N/mm^2, than OP, which was 1529.2 N/mm^2. The difference is a result of the natural mechanical properties of cardboard and office paper, which is described in the section of materials, due to the higher strength of CB than OP.

Another important property of wood-based products for use in furniture design is screw withdrawal resistance, the purpose of which is to find out if the material is strong enough to hold screws inside. The testing of screw withdrawal resistance was done on both the face of the board and the edge of the board. The screw withdrawal resistance on the face of the board was 316.6 N for the CB material and 347.2 N for the OP material, while the edge resistance was 170.9 N for the CB material and 160.6 N for the OP material. In comparison with industrially manufactured boards such as MDF boards where the resistance for 18 mm board is higher than 1080 N (EN 320, 2011), the results were much lower. The reason can be attributed to the mechanical properties of paper in general, which was described in the material part of this article.

Table 3. Mechanical Properties of the CB

CB								
Testing Method	Mean	Geometric Mean	Minimum	Maximum	R	Median	Variance	Standard Deviation
MOR (N/mm²)	8.45	8.24	5.02	10.82	5.80	8.62	3.09	1.76
MOE (N/mm²)	1931.32	1902.75	1215.05	2231.47	1016.42	2047.49	94365.23	307.19
Internal Bond (N/mm²)	7.70	6.90	1.90	13.53	11.63	7.10	10.30	3.21
Screw Withdrawl Resistance-Surface (N)	316.59	298.38	150.12	581.44	431.32	284.43	12277.43	110.80
Screw Withdrawl Resistance-Edge (N)	170.93	149.35	23.77	366.04	342.27	169.43	5813.25	76.24

Table 4. Mechanical Properties of the OP

OP								
Testing Method	Mean	Geometric Mean	Minimum	Maximum	R	Median	Variance	Standard Deviation
MOR (N/mm²)	4.91	4.71	1.98	6.57	4.59	5.32	1.38	1.17
MOE (N/mm²)	1529.22	1458.89	582.90	1992.47	1409.57	1681.84	151545.65	389.29
Internal Bond (N/mm²)	3.53	3.39	1.33	7.70	6.37	3.35	2.69	1.64
Screw Withdrawl Resistance-Surface (N)	347.91	325.33	128.63	588.96	460.33	353.37	13105.07	114.48
Screw Withdrawl Resistance-Edge (N)	200.75	182.11	85.98	490.04	404.06	197.05	8168.86	90.38

The internal bonding is also very important property of wood-based products to have strong joints between each other in the use of furniture made from board material like MDF boards or particleboards. The internal bond test values of the CB and OP samples averaged 7.70 and 3.53 N/mm^2, respectively. However, the CB samples had a larger range than the OP samples. The internal bond ranged from 1.90 to 13.35 N/mm^2 for the CB samples and 1.33 to 6.55 N/mm^2 for the OP samples. According to the EN standard 312 (2010), the minimum internal bond value for boards with a thickness of 18 mm or less that are used for interior fitments (including furniture) in dry conditions (Type P2) is 0.35 N/mm^2. The reason why CB had higher range of internal bond than OP is due to the mechanical properties of cardboard. The cardboard has bigger fibers and there was added glue already. On the other hand, office paper is bleached in order to have white color and the fibers thereby lose some of their strength.

The data were analyzed statistically with one-way factor ANOVA, Tukey HSD test, and regression analysis. The statistical analysis showed a positive correlation between the MOR/MOE and the density. The linear regression between the MOR and the density (Fig. 5) showed a small statistically significant dependence (R = 0.5074). As seen in Fig. 6, the correlation coefficient for the MOE and the density was 0.8149. The higher the density the higher the Young's modulus. No other correlations were observed in the analysis.

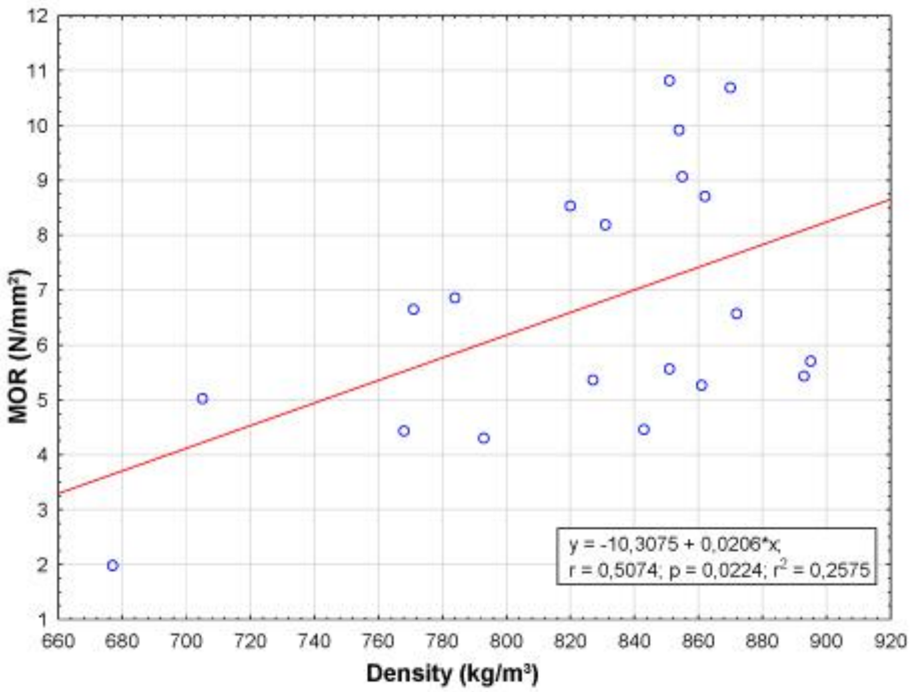

Fig. 3. The linear regression between the MOR and the density

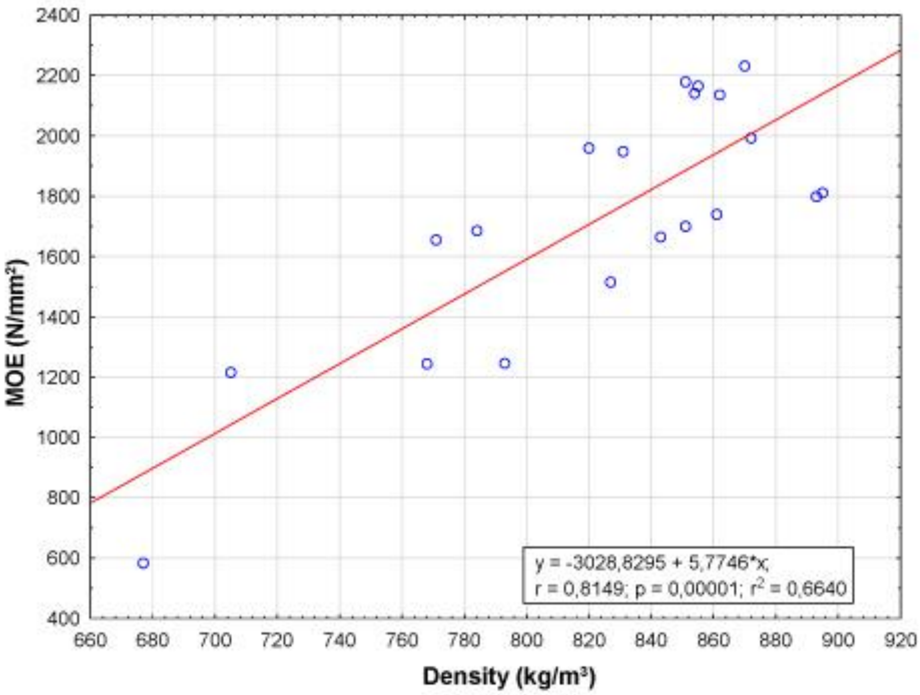

Fig. 4. The linear regression between the MOE and the density

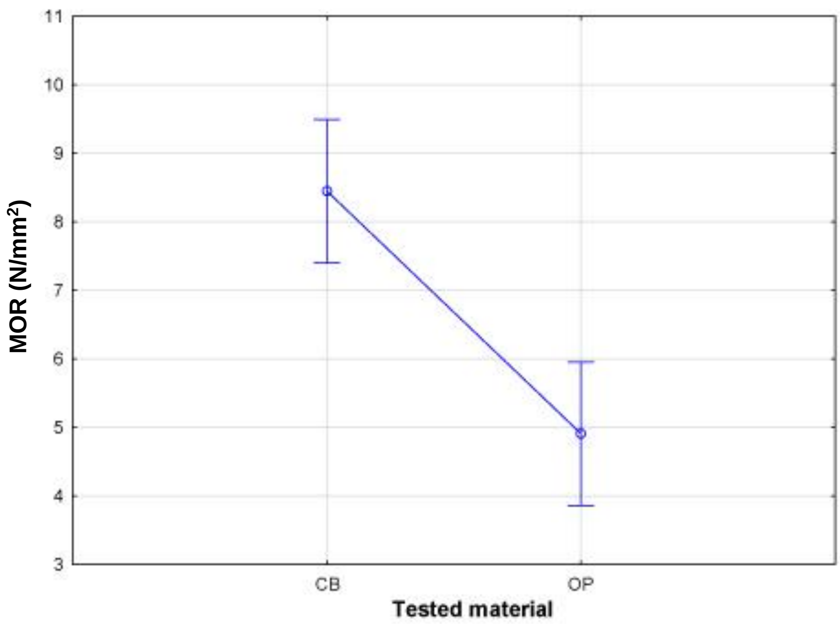

Fig. 7. The one-way factor ANOVA for the MOR of the CB and OP materials

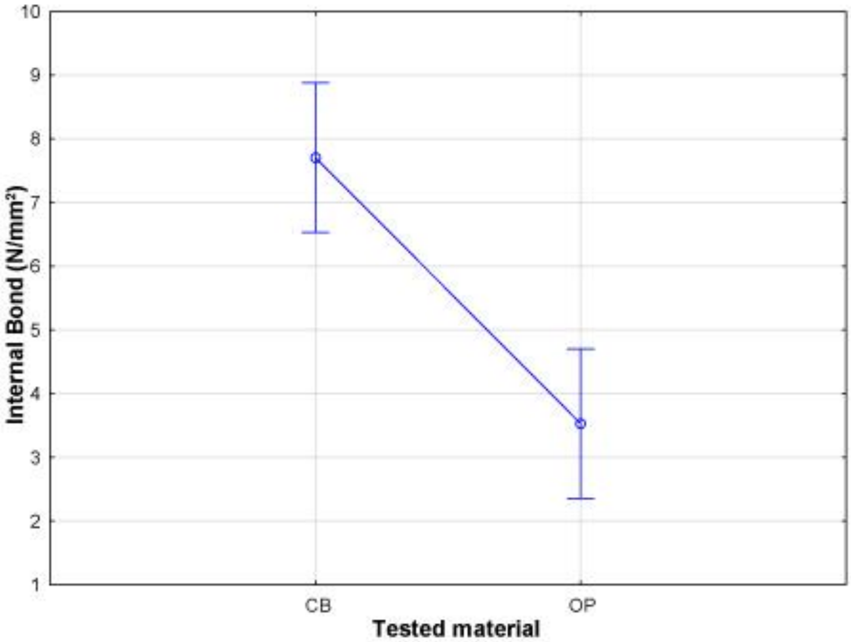

Fig. 8. The one-way factor ANOVA for the internal bond of the CB and OP materials

As can be seen in Figs. 7 and 8, the ANOVA results showed that the CB had a higher MOR and internal bond value than the OP. It was observed that material A (CB) had higher values than material B (OP). The reason could be better mixed substances in the mixture and higher strength of cardboard in comparison with regular office paper, which is weakened by bleaching process. The Tukey HSD values for the MOE and the internal bond were 0.025 and 0.0001, respectively. According to Tukey test HSD for MOE and internal bond (Table 3 and 4) it can be concluded that there was a statistically significant difference between material A (CB) which had higher values than material B (OP). The MOE of CB was higher than MOE of OP. Also, in case of internal bond there was a statistically significant difference - material A (CB) had higher internal bond than material B (OP).

CONCLUSIONS

1. Cardboard (CB) exhibited better physical and mechanical properties than regular office paper because of its manufacturing process.
2. The CB and office paper (OP) post-consumer paper can be used to produce paper-polylactic acid (paper-PLA) boards as another option for wood-based products, for example as a desktop or the top of a small table.
3. The boards are manufactured in a sustainable and circular way because they can be recycled (milled) again and the new boards can be manufactured.

ACKNOWLEDGMENTS

This project was supported by the Specific University Research Fund of the FFWT Mendel University in Brno. It is part of the project IGA LDF_VP_2019009. The authors would like to thank to Mendel University's Department of Furniture, Design and Habitat and the Department of Wood Science and Technology for the facilitating the use of their equipment. The authors are also thankful for the assistance and previous research of Salzburg University of Applied Sciences.

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Article submitted: November 11, 2020; Peer review completed: March 6, 2021; Revised version received and accepted: April 14, 2021; Published: April 16, 2021.
DOI: 10.15376/biores.16.2.3952-3963