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THE INVESTIGATION OF PROPERTIES OF BLOCKBOARDS MADE OF POST-CONSUMER WOOD

Today in woodworking, there are problems with the use of wood waste and the accumulation of involved wood as an additional and not fully used resource. The problem has not been completely solved, as there is no scientific basis and practical recommendations for efficient production processes with predicting the properties of products made from Post-Consumer Wood (PCW), in particular in the production of blockboards (BB). The objective of the studies is to substantiate and develop a scientific and technical basis for resource-saving and environmentally friendly technologies, to establish the influence patterns of PCW properties on the mechanical characteristics of the products obtained, to develop operating parameters and to formulate practical recommendations, confirmed by the results of experimental studies. The studies have proved the expediency of using PCW in technological processes of woodworking, in particular in the production of construction materials - blockboards with predicted characteristics. In order to rationally use raw materials for the manufacture of conventional blockboards made from Post-Consumer Wood (PCW-BB), new designs of a conventional PCW blockboard with a thickness of 22 mm and with a unified strip width of 16, 32, 48, and 64 mm, the strips are glued ones, 3 mm thick, and faced with plywood on both sides. The authors of the article found that in order to ensure improved operating characteristics of the blockboards, it is important to lay radial, semi-radial and tangential strips in structures with the ratio of width to thickness of the cross-sections of the strips - rationally and efficiently - 1:1, 2:1, 3:1. Substantiation on this basis of new designs of PCW blockboards makes it possible to reveal shortcomings of these products at the conceptual stage of the project and correct them before manufacturing taking into account the specified technical conditions and reducing costs at the development stage. Mathematical models for predicting the main characteristics of conventional PCW blockboards (PCW-BB) have been constructed, which made it possible to determine the indexes of the bending strength of the BB across the strips, σ_{BB} , and the shear strength of the BB along the glue line, τ_{BB} . The coefficients of approximation of mathematical dependencies for predicting the strength of PCW-BBs, the strips of which were made of fir wood, were calculated, which would allow for the selection of rational designs of blockboards with appropriate characteristics. It has been established that the developed mathematical models make it possible to

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predict the characteristics of the PCW-BB depending on the cross-sectional dimensions of the strips, the angle of the annual rings slope to the blockboard face and the age of the PCW, and, on this basis, to propose improved designs of these blockboards for the technological processes of woodworking. The influence patterns of the properties of structural elements on the indicators of conventional PCW-BB (500 × 500 × 22 mm) were experimentally established. It was found that an increase in the width of the strips leads to a decrease in the strength indexes (by 29-37%); an increase in the angle of the annual rings slope to the BB face leads to an increase in static bending strength (by 31-33%) but to a decrease in shear strength (by 4-7%); an increase in the age of the PCW leads to a decrease in strength indexes (by 3-8%). It was found that the physical and mechanical parameters of the experimental PCW-BBs with a strip cross-sections of 1:1, 2:1, 3:1 meet the requirements of the standard (larger values: for static bending of a rate of 15 MPa and for shearing at a rate of 1 MPa), and for the 4:1 cross-section, they partially had lower indexes by 2-3%. To ensure the strength of the developed structures of the PCW-BBs, it is recommended to use the 3:1 ratio of the sides in the cross-section of the strips, and the slope of the annual rings to the blockboard face must be at least 45°. It was found that the deviation of the values obtained by mathematical models in determining the strength in static bending and shearing in comparison with the experimental ones did not exceed 8% and 10%, respectively.

Keywords: post-consumer wood, blockboards, mathematical model, physical and mechanical properties, characteristics, strength, recycling, technology, use

Introduction

Two problems – the problem of raw materials and the problem of waste management – are the most relevant issues in the woodworking industry in the world, Europe and Ukraine, particular, at the beginning of the 21th century [Gayda 2007]. A partial solution to the latter is a rational and comprehensive approach to reducing the former – the problem of raw materials.

Nowadays, an unused wood raw materials base and a really potential resource, the size of which increases with the development of manufacturing and processing industries, are the stock of post-consumer wood [Marutzky 1996c, 2003; Onisko and Dobrowolska 1997; Ratajczak et al. 2003a; Ratajczak and Szostak 2003b; Lykidis and Grigoriou 2005; Mantau et al. 2005a, 2005b; Gayda 2011a, 2012, 2013, 2016; Gworek 2016; Ratajczak et al. 2018].

Post-consumer wood (PCW) is used wood and any products made from it that do not have their further use according to their original purpose and are subject to recycling in order to protect the environment and human health or to re-involving them in economic activity as raw materials or/and energy resources.

According to the large-scale European project COST Action E31 [2007], the definition of *post-consumer wood* (PCW) is interpreted as follows: “Recovered Wood (“post-consumer wood” or “post-use wood”) is demolished solid products

biomass (examples: used construction biomass, used pallets biomass) and used products biomass that is going to be used in the same product for another purpose (example: used railway sleepers), generated from used solid wood products”. “The term Recovered Wood does not cover biomass in used solid wood products that is going to be used once more in a new setting (example: wooden chair), or biomass in intermediate solid wood products that is going to be used in new solid material products (example: used panel boards)”. That is, post-consumer wood is all kinds of wood (woody biomass), available after the completion of the existence of primary products.

On March 1, 2003, the European Union adopted the regulatory document AltholzV [2002, 2003a, 2003b], which prohibits the removal of environmentally questionable and harmful resources to landfills, and obliges wood product manufacturers to think about future disposal of products that ended their useful life. According to scientists Michanicki [1996, 1997], Grigoriou [1996, 1998], Boeme [2003], Erbreich [2004], Garg and Singh [2004], Lykidis and Grigoriou [2005], Werner et al. [2007] decomposition of contaminated PCW is very destructive to the environment due to the content of harmful substances such as glue, halogenated substances in coatings (in particular PVC films), antiseptics, flame retardants, etc.

Polish scientists Ratajczak and Szostak [2003c] and Wróblewska and Cichy [1997] argue that all wood waste should be divided into clean and polluted.

The PCW accounting was carried out by Danecki and Rodzeń [1997], Danecki [2003], Ratajczak et al. [2003a] who noted that back in 2002 the potential amount of PCW, in particular in Poland, was 2.8 million tons. The volume of used wood is quite significant in Western Europe. In Austria, its volumes may annually reach about 1.0 million tons [Brandstätter 1994]. This figure for Germany was already a reality 30 years ago, and data from other years indicate a much higher volume of PCW. As early as 1996, Marutzky [1996a, 1996b] estimated the volume of PCW formation in Germany at 8.0 million tons, and the scientists Mantau et al. [2005b] voiced in 2003 data on the volume of PCW at the level of 6.531 million tons. The scientist Ratajczak [2013] believes that the rational management of secondary timber resources should be based on the cascading use of the raw material model – the gradual re-transformation of the resource into suitable products. If the products are not suitable – only then they may be burned. The researcher Marutzky [2003] back in 1995 argued that PCW would primarily be used in the manufacture of particleboards. Today, approximately 20% to 25% of PCW is used in the production of particleboards.

Glued wood structures made of anisotropic strips (spliced or solid strips) have strength characteristics and deformability indices that are decisive in the design of new wood products. Scientists have given much attention to the physico-mechanical properties and shape stability of glued boards made from primary wood [Pardaev 2009; Kryvyk et al. 2012; Kiyko 2014 and others] but not to the blockboard study, and especially those made from PCW.

The problem of blockboard strip width is still debatable today. Thus, scientists Maevskyy and Benyakh [2005] in the study of glued oak wood panels for the manufacture of front surfaces, recommend the use of 40 mm wide strips at an angle of slope of 68° to the blockboard face, and when using only radial strips, the maximum width can be 67.9 mm.

Pardaev [2009] in the study of glued panels made from primary wood (pine) offers a thickness-to-width ratio in the cross section of the strips 1:2,5-2,8 with an angle of slope within the range between 40° and 50° to the blockboard face. To date, laborious research has been done on the possibility of using solid PCW in the field of woodworking for the manufacture of structural materials, in particular for the manufacture of blockboards (BB). However, there are still weak spots here, and in some studies, the problem has not been studied enough.

The results of the analysis of the above studies show that this problem has not been completely resolved, since the scientific basis and practical recommendations for efficient production processes with predicting the properties of products made from PCW have not been developed, in particular, in the production of blockboards (BB). Thus, the substantiation and establishment of the influence patterns of the PCW parameters on the mechanical characteristics of the products obtained, the development of new designs of PCW blockboards and providing practical recommendations, confirmed by the results of experimental studies, is an urgent scientific and technical problem of our time, which is of great importance.

Therefore, the purpose of scientific work in this article is the investigation of the properties of blockboards made of post-consumer wood.

Main objectives:

- to propose new designs of blockboards and to develop mathematical models for predicting the main characteristics of conventional PCW blockboards: static bending strength and shear strength depending on the width of the strip, the angle of the annual rings slope to the blockboard face, and the age of the PCW.
- to experimentally determine the physical and mechanical characteristics of conventional PCW blockboards and compare the strength indexes with the data obtained by mathematical dependencies.

Solving the set tasks will allow PCW to be involved in the technological processes of woodworking, in particular for the production of structural materials - blockboards with predictable characteristics.

Materials and methods

The blockboard panels in this study were manufactured by using the following materials:

- structural wooden elements from the dismantled house (demolition wood),
- wooden bars and rails from used window and door casings (Fig. 1),

- three-ply plywood (3 mm) from used furniture pieces,
- polyvinylacetate glue (PVA glue of the Jowat 103.05 brand).

This wood was not dissimilar in outward appearance to primary wood, although it was about 1-20 years old. Experimental and theoretical studies were carried out by applying a system approach using computers and the existing software.

This paper uses the following methods:

- physical and mechanical – to determine the size of the PCW-BB and indexes of their physical and mechanical characteristics,
- mathematical theory of planning experiments – to establish dependencies and analyze them,
- mathematical statistics – for processing the results of experimental studies.



Fig. 1. Post-consumer wood to be used for manufacturing blockboards

Theoretical research on the problem

Development of constructions of the PCW-BB

The research on the material use of PCW was based on the developments devoted to the manufacture of high-quality blockboards with the predicted characteristics of various designs (Fig. 2).

The determining input components (geometric and physical characteristics) that will affect the physico-mechanical characteristics of the PCW-BB are:

- K_p – the width/thickness ratio of the strip (code: 1 – 1:1; 2 – 2:1; 3 – 3:1; 4 – 4:1) $K_p = a/h$ (Fig. 3);

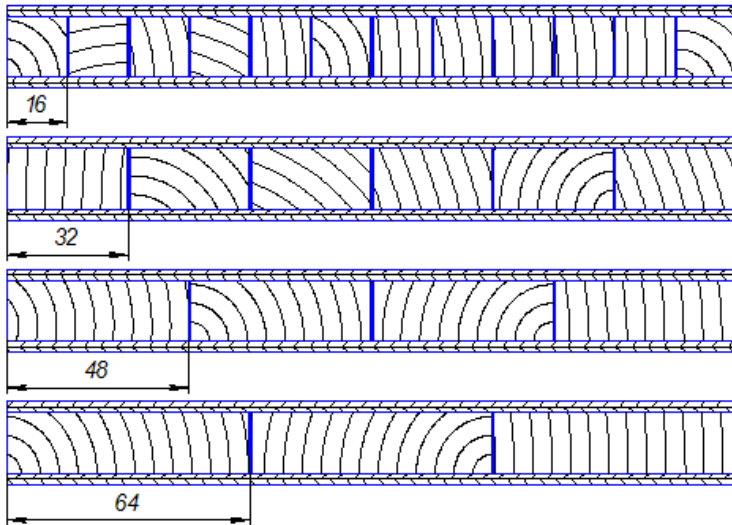


Fig. 2. Proposed structures for the PCW-BB panels, to be investigated

K_α – the slope of annual rings of strips (code: 1 – 61-90°; 2 – 31-60°; 3 – 1-30°) $K_\alpha = 90/\alpha$ (Fig. 4);

K_N – PCW age (the lifetime of the product) (code: 1 – 0; 2 – 1-5; 3 – 6-10; 4 – 11-15; 5 – 16-20).

The age of PCW was determined in two ways:

1. For used furniture – by labels (tags) glued by the producers which indicated the time of manufacturing.
2. For joinery products – according to a survey on the time of constructing.

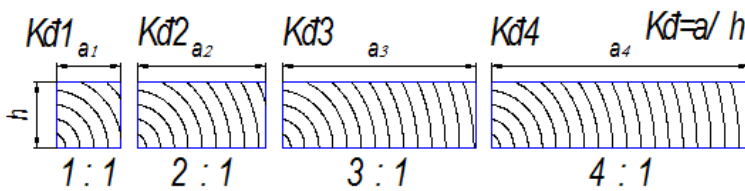


Fig. 3. The width/thickness unified ratios of the strip

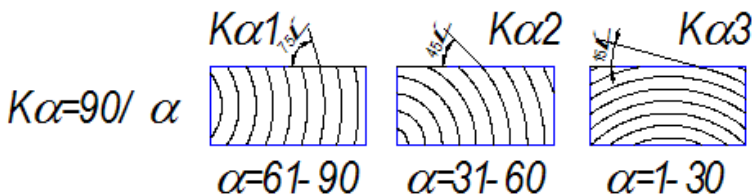


Fig. 4. Types for strips of cross-sections of different angles of the annual rings slope to the blockboard face

Construction of mathematical models for predicting the characteristics of PCW blockboards

Taking into account the results of theoretical studies and the results of long-term experimental studies, as well as the nature of the change of characteristics, mathematical exponential dependences were calculated and proposed to predict the characteristics of PCW blockboards (the functions of the research results were approximated). Based on the numerical methods of mathematical modeling, an engineering solution to the problem of predicting the characteristics of PCW blockboards was obtained. General view of mathematical models for predicting the characteristics of PCW blockboards [Gayda 2015]:

BB strength in bending across the BB strips (σ_{BB}) (norm 15 Mpa)

$$\sigma_{BB} = A \cdot \exp(-B \cdot \sigma \cdot K_{NPCW}) \cdot \exp(-C \cdot K_p) \cdot \exp(-D \cdot K_\alpha) \quad (1)$$

BB shearing strength along the glue line (τ_{BB}) (norm 1 Mpa)

$$\tau_{BB} = A \cdot \exp(-B \cdot \tau \cdot K_{NPCW}) \cdot \exp(-C \cdot K_p) \cdot \exp(-D \cdot K_\alpha) \quad (2)$$

where: A, B, C, D are approximation coefficients of exponential dependence;
 σ is the static bending strength of PCW of a certain species by the slope angle of the annual rings to the blockboard face, MPa;
 τ is the shearing strength of PCW of a certain species by the slope angle of the annual rings to the blockboard face, MPa;

Types of experimental tests – methods of experimental research

The general research methodology covers the methods for manufacturing a blockboard from PCW and the methods for determining the characteristics of the PCW blockboard, in particular, its static bending strength and shearing strength. Since the research was based on the study of the influence of the characteristics of the BB structural components on the bending strength and shearing strength, we fabricated PCW blockboards in accordance with the methodological research grid (Table 1).

Table 1. Methodical grid of experimental studies on PCW blockboards

Input factors – coefficients					
PCW age	Annual rings slope	Strip cross-section – thickness-to-width ratio			
$K_{N1}; K_{N2}; K_{N3};$ $K_{N4}; K_{N5};$	$K_{\alpha 1}$	K_{p1}	K_{p2}	K_{p3}	K_{p4}
	$K_{\alpha 2}$	K_{p1}	K_{p2}	K_{p3}	K_{p4}
	$K_{\alpha 3}$	K_{p1}	K_{p2}	K_{p3}	K_{p4}

The design of PCW blockboards envisages the use of strips of the same wood species. The PCW- blockboards were manufactured using glued strips (GS type). All BBs were manufactured with a thickness of 22 mm in accordance with GOST 13715:1978 and ISO 13609-2014. The width of the strips was 16, 32, 48 and 64 mm, and the thickness after milling of the blockboards on a thicknessing planer on both sides was 16 mm. To compare the obtained results, a blockboard from fresh wood was also manufactured, that is, with an age coefficient of 0 years.

Based on the methodological grid of experimental studies, in particular the number of variable factors ($K_\alpha = 3$, $K_p = 4$, $K_N = 5$), $3 \times 4 \times 5 = 60$ types of PCW blockboards were manufactured

Technology of obtaining the PCW-BB

The manufacturing procedure for BB from PCW involves the following steps: clearing the used wood off ironmongery and other foreign inclusions; breaking finger joints and making trims to remove defects; removing of finish coating from the wood surface (varnish, paint); face planing; length cutting of the wood; double-edge profiling; trimming to size; gluing of variously-constructed BB (Fig. 5); cutting of plywood, laying plywood on the core-board under pressure; cutting to size; sanding. Strips moisture content – $8 \pm 2\%$; moisture differences among the wood strips – $2 \pm 1\%$; the moisture content was controlled by the device S200; polyvinylacetate glue (PVA glue of the Jowat 103.05 brand).

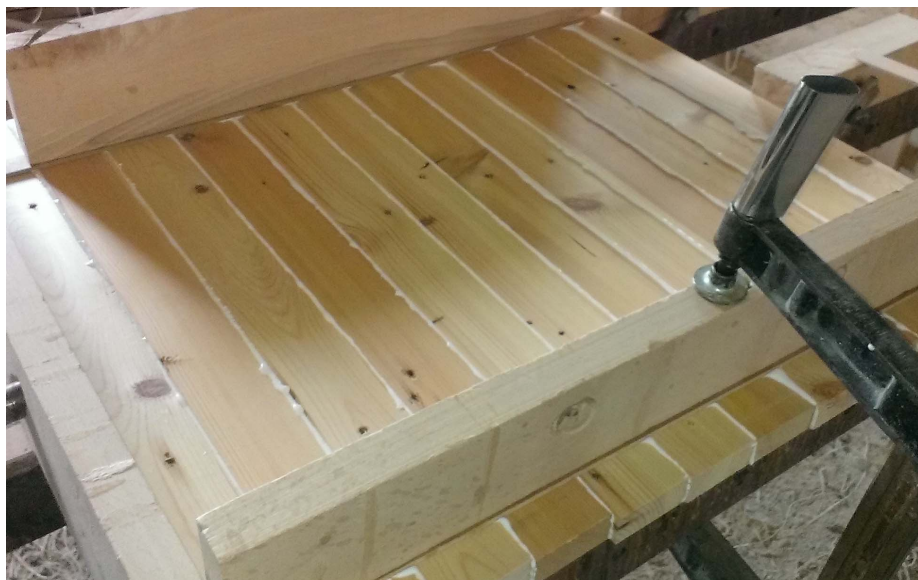


Fig. 5. The process of manufacturing a BB shield

Preparing the blockboard core involves selection of strips according to the strip width, annual rings angle, applying glue to the strips edges with the glue spread of 200-250 g/m², clamp bonding (operation parameters: temperature – 85-90°C; soaking time – 30-40 min; pressure – 0.5-1.0 MPa), technological conditioning (humidity – 60 ±5%; temperature – 20 ±2°C) for 8-12 hours; double-side milling up to 16 mm; dimension cutting into a size of 520×520 mm.

The final stage of the PCW BB comprises the following steps: application of glue to the blockboard core with glue spread of 150-200 g/m², the formation of package, facing in a flat press (operation parameters: temperature – 115-120°C; press time – 4-6 min; pressure – 1.2-1.3 MPa), technological conditioning (humidity – 60 ±5%; temperature – 20 ±2°C) for 4-8 hours; cutting on the perimeter into dimension of 500 × 500 mm (Fig. 6).



Fig. 6. The view of the experimental PCW-BB

Methods of preparing test specimens

Specimens selection, their quantity, making and preparing for testing was done according to GOST 9620:1994 and DIN EN 326-1:1994. Test specimens for determination of static bending strength across strips were made according to GOST 9625:2013 which refers to GOST 13715:1978 and ISO 13609-2014. The specimen's thickness is equal to the thickness of the BB, that is 22 mm. The width of the specimen $b=50$ mm, and, the length $l_l = 15 h = 15 \cdot 22 = 330$ mm (Fig. 7).

Test specimens for determination of shearing dry strength along glue line, were made according to GOST 9624:2009 and ISO 12579-2007.

The shape and dimensions of test specimens for determination of shearing strength along glue line should correspond to the 85 × 40 × 22 mm dimensions with the kerf of 5 mm (Fig. 8).



Fig. 7. Specimens of veneered BB with the core-board from PCW to test the static-bending strength across strips

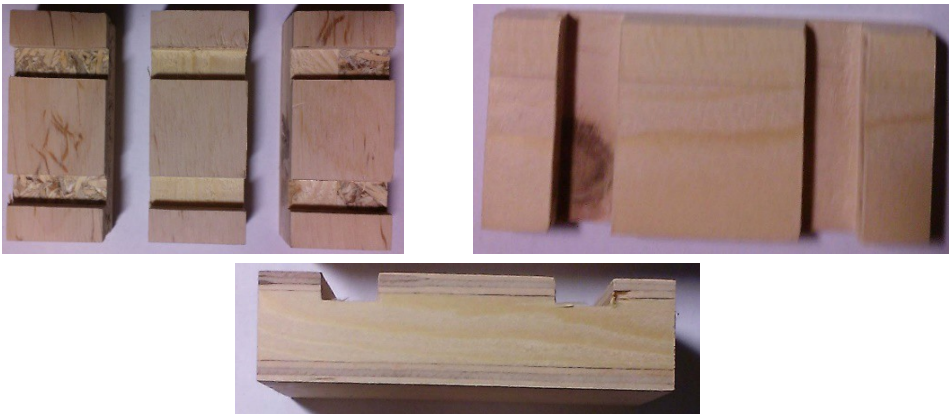


Fig. 8. Specimens of veneered BB with the core-board from PCW to test the shearing strength along glue line

Description of methods of investigation

To suit GOST 13715:1978, ISO 13609-2014, PN-76/D-97000, DIN 68705-2:2016-03 for BB the definition of such physical and mechanical characteristics is regulated: static-bending strength across strips and shearing strength along glue line

To measure the strength of the BB on static-bending strength across strips, the recommendations described in GOST 9625:2013 and PN-EN 310:1994 were followed.

Static bending strength (σ_{BB}) in MPa was calculated by the formula:

$$\sigma_{BB} = \frac{3 P_{\max} l}{2 b h^2} \quad (3)$$

where: P_{\max} – maximum load, H; l – spacing between supports, mm; b – the width, mm; h – the specimen thickness, mm.

The strength along glue line τ_{BB} is determined in MPa by rounding the result to 0.05 MPa by the formula:

$$\tau_{BB} = \frac{P_{\max}}{b_{sh} \cdot l_{sh}} \quad (4)$$

where: P_{\max} – maximum load, H; b_{sh} , l_{sh} – the width and the length of the shear area, mm.

According to GOST 28840:1990 in order to determine static bending strength across strips, the laboratory test machine IP5057-50 (maximum load – 50 kN) (fig. 9) was used while the test machine YMM-5 was used to determine shearing strength with a measurement error of 1%.



Fig. 9. The laboratory test machine IP5057-50 (maximum load – 50 kN)

Results and discussion

Results of development of mathematical models

In order to determine the indexes of static bending strength and shearing strength of the PCW blockboard, in addition to the data of these studies, we used the results of previous studies on the parameters of strength and panel structures [Gayda 2010, 2011b, 2018].

To determine the approximation coefficients, the Microsoft Office Excel program and the least squares method were used. To select the optimal structure of the functional dependence model, we used the determination coefficient R^2 as the value of the approximation reliability, which indicates how well the obtained observation results confirm the model. The approximation coefficients of the model were defined to predict the bending strength in the following form: $A = 42.36$; $B = -0.0204$ (-0.0002σ); $C = -0.115$; $D = -0.156$, where σ is the bending

strength of the strips made from PCW of a certain age group. Similarly, the approximation coefficients of the model for predicting the shearing strength were determined: $A = 2.016$; $B = -0.0226$ ($B = -0.0027\tau$); $C = -0.15$; $D = -0.027$, where σ is the shearing strength of the strips made from PCW of a certain age group.

Taking into account the values of the approximation coefficients, the mathematical dependences of blockboards made from fir-species PCW will take the form:

a) The mathematical dependence of the strength in bending across the strips, σ_{BB} , for blockboards with a thickness of 22 mm from glued strips (GS type), made from fir wood, lined with 3 mm plywood, takes the form:

$$\sigma_{BB} = 42.36 \cdot e^{-0.0002 \cdot \sigma \cdot \text{KNPCW}} \cdot e^{-0.115 \cdot K_p} \cdot e^{-0.156 \cdot K_H} \quad (5)$$

b) The mathematical dependence of the shearing strength along the glue line, τ_{BB} , for blockboards with a thickness of 22 mm from glued strips (GS type), made from fir wood, lined with 3 mm plywood, takes the form:

$$\tau_{BB} = 2.016 \cdot e^{-0.0027 \cdot \tau \cdot \text{KNPCW}} \cdot e^{-0.15 \cdot K_p} \cdot e^{-0.027 \cdot K_H} \quad (6)$$

Results of the experimental test

Influence of the characteristics of the PCW-made strips on the bending strength of the blackboards (BB)

According to the results of the experiment (Fig. 10, Fig. 11) and processing of the test data, graphical dependences (Figs. 12-14) were obtained of the effect of the ratio of the width to the thickness of the strip, the slope of the annual rings at the ends of the strips and the age of the PCW strips on the strength of the blockboard (Table 2).



Fig. 10. Test specimen of the PCW-BB for bending strength at the moment of load



Fig. 11. The nature of the destruction of the specimens of the PCW-BB during the bending strength test

Table 2. The bending strength of the PCW-BB across the strips, MPa

PCW age	K_{p1}			K_{p2}			K_{p3}			K_{p4}		
	$K_{\alpha30}$	$K_{\alpha60}$	$K_{\alpha90}$	$K_{\alpha30}$	$K_{\alpha60}$	$K_{\alpha90}$	$K_{\alpha30}$	$K_{\alpha60}$	$K_{\alpha90}$	$K_{\alpha30}$	$K_{\alpha60}$	$K_{\alpha90}$
0	22.58	27.05	31.32	20.53	25.32	28.91	18.21	22.89	25.92	15.05	19.84	22.17
5	22.31	26.32	30.38	20.28	24.64	28.05	17.99	22.27	25.15	14.87	19.30	21.51
10	22.07	25.76	29.65	20.06	24.11	27.37	17.80	21.80	24.53	14.71	18.89	20.99
15	21.99	25.46	29.23	19.99	23.83	26.98	17.73	21.54	24.19	14.66	18.67	20.69
20	21.81	25.16	28.83	19.83	23.55	26.61	17.59	21.29	23.86	14.54	18.45	20.41

It was found that the highest index of strength in static bending (31.32 MPa at a rate of 15 MPa) is characteristic of PCW-BB of the following structures: the ratio of the cross-sectional dimensions of the strips K_{p1} (1:1) with the annual rings slope to the blockboard face $K_{\alpha1}$ (61-90°), at the age of the PCW K_{N1} (0), and the lowest (14.54 MPa) - at K_{p4} (4:1) with the annual rings slope to the blockboard face $K_{\alpha3}$ (1-30°), at the age of the PCW K_{N5} (16-20). This indicates that the radial strips in the blockboard structure offer greater resistance to destruction than tangential ones. The physical and mechanical parameters of the experimental PCW-BB with a cross-section of strips 1:1, 2:1, 3:1 meet the requirements of the standard (larger values: for static bending at a rate of 15 MPa), and for a cross-section of 4:1 partially had lower indexes up to 3%. Thus, as can be seen in Figures. 12-14, increasing the strip width leads to a decrease in static bending strength, σ_{BB} . Graphic interpretation shows that a decrease in the angle of the annual rings slope to the blockboard face and increasing the age of the PCW results in a decrease in static bending strength (Fig. 15).

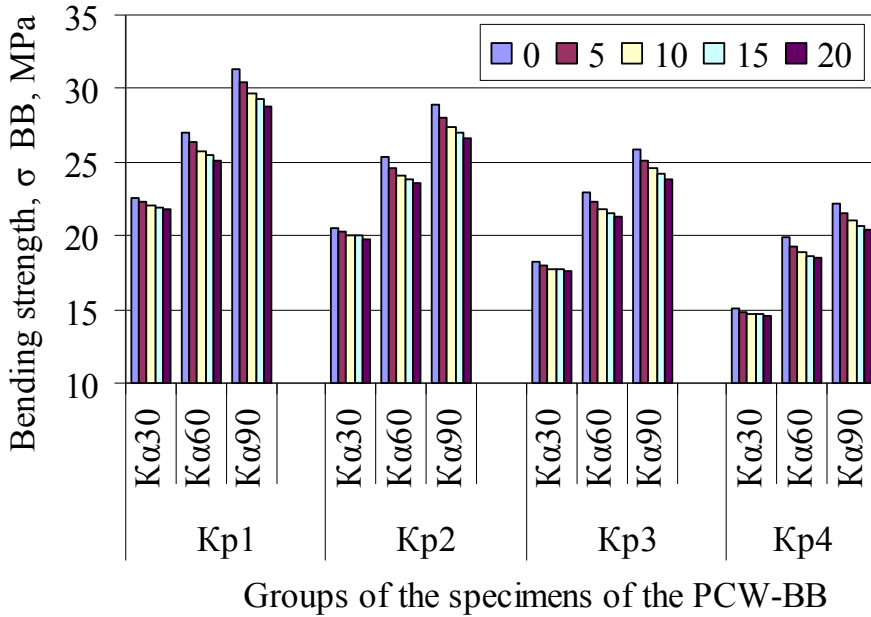


Fig. 12. The results of the PCWBB static bending strength (K_p – the thickness-to-width ratio of the strip; K_α – the slope of annual rings of strips; K_N – PCW age (the lifetime of the product))

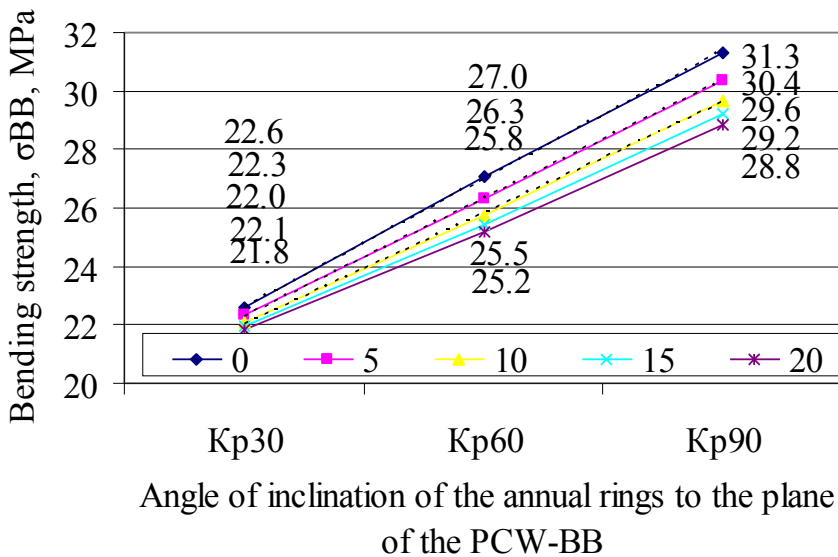


Fig. 13. Graphic dependencies $\sigma_{BB} = f(K_\alpha, K_N)$ at the cross section of the strip 16×16 (K_{p1})

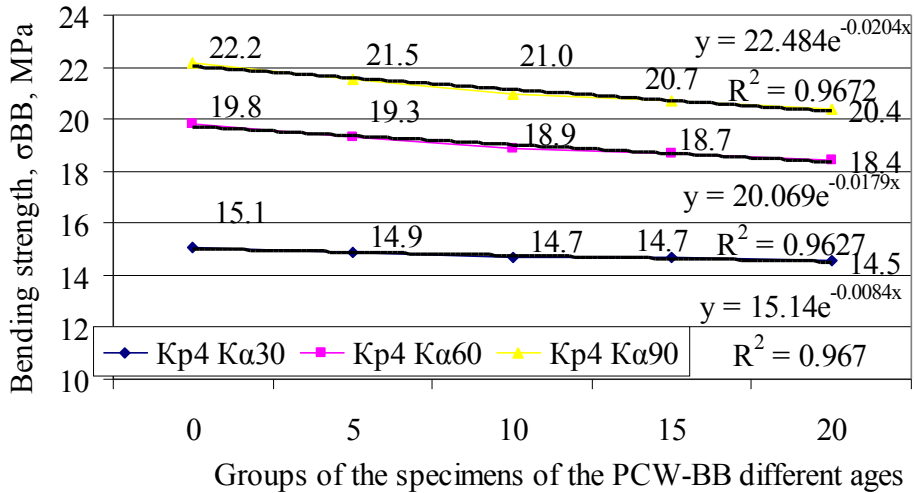


Fig. 14. Graphic dependencies $\sigma_{BB} = f(K_{\alpha}, K_N)$ at the cross section of the strip $64 \times 16 (K_{p4})$

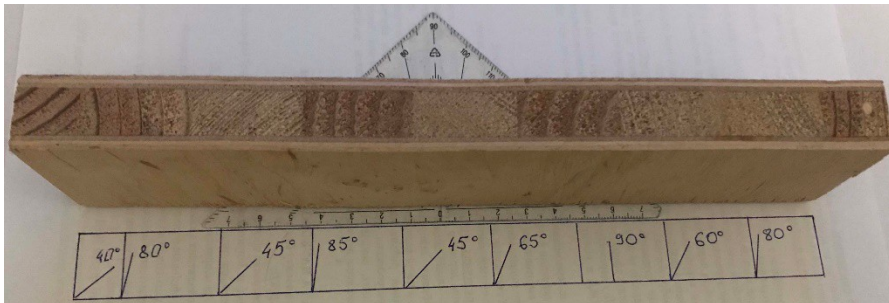


Fig. 15. Measuring the angles of annual rings slope at the ends of the strips to the face of the PCW using an angle protractor

Influence of PCW-made strips characteristics on the shear strength of the blockboards (BB)

According to the results of the experiment (Figs. 16, 17) and data processing, graphical dependences (Figs. 18-20) were obtained of the effect of the thickness-to-width ratio of the strip, the slope of the annual rings at the ends of the strips, and the age of the PCW-made strips on the strength of conventional blockboards (Table 3).

The highest index of shear strength along the glue line (1.71 MPa at a rate of 1 MPa) is characteristic of PCW-BB of the following design: the cross-sectional dimensions of the strips K_{p1} (1:1) with the annual rings slope to the blockboard face $K_{\alpha3}$ (1-30°) at the age of the PCW K_{N1} (0), and the lowest index (0.97 MPa) at K_{p4} (4:1) with the annual rings slope to the blockboard face $K_{\alpha1}$ (61-90°), at

the age of the PCW K_{N5} (16-20). It can be seen that the tangential strips adhere better (have greater adhesion) to the facing than the radial ones.

Table 3. Shear strength of the PCW-BB along the glue line

PCW age	K_{p1}			K_{p2}			K_{p3}			K_{p4}		
	K_{a30}	K_{a60}	K_{a90}	K_{a30}	K_{a60}	K_{a90}	K_{a30}	K_{a60}	K_{a90}	K_{a30}	K_{a60}	K_{a90}
0	1.71	1.66	1.64	1.41	1.35	1.31	1.20	1.14	1.11	1.10	1.05	1.02
5	1.65	1.63	1.61	1.36	1.32	1.29	1.16	1.12	1.09	1.07	1.03	1.00
10	1.60	1.60	1.59	1.32	1.29	1.27	1.13	1.10	1.08	1.04	1.01	0.99
15	1.58	1.58	1.58	1.30	1.28	1.26	1.11	1.08	1.07	1.02	1.00	0.98
20	1.56	1.57	1.57	1.29	1.27	1.26	1.10	1.08	1.06	1.01	0.99	0.97



Fig. 16. Test specimen of the PCW-BB for shear strength at the moment of load

It was determined that the physical and mechanical parameters of the experimental PCW-BB with a strip cross-section of 1:1, 2:1, 3:1 meet the requirements of the standard (larger for shearing at a rate of 1 MPa), and for a cross-section of 4:1, they partially had lower indexes by 2-3%. Therefore, as can be seen in Figures 18-20, increasing the width of the strips leads to a decrease in shear strength, τ_{BB} . A decrease in the angle of the annual rings slope to the blockboard face and an increase in the age of the PCW leads to a decrease in shear strength. An increase in age slows down the dynamics of reducing the effect of annual rings on the shear strength index. With the age of PCW being 15-20 years, there is practically no effect (Fig. 20).

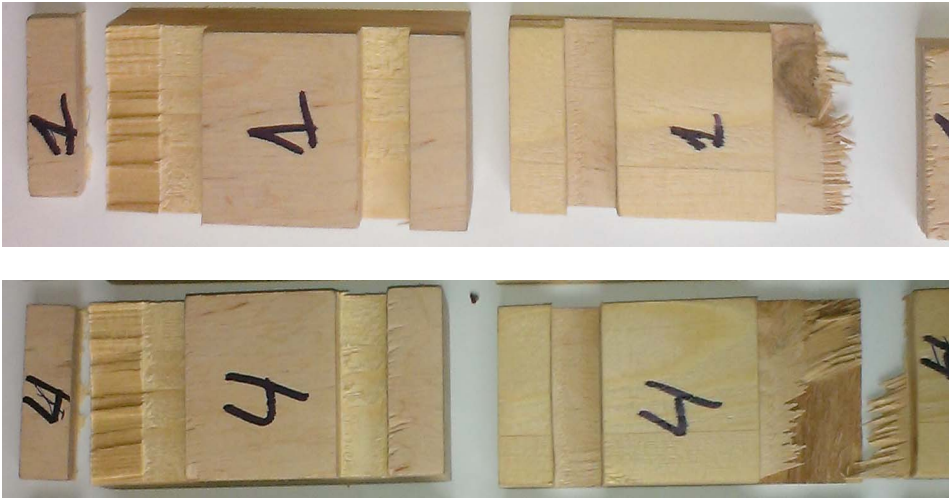


Fig. 17. The nature of the destruction of the specimens of the PCW-BB during the shear strength test

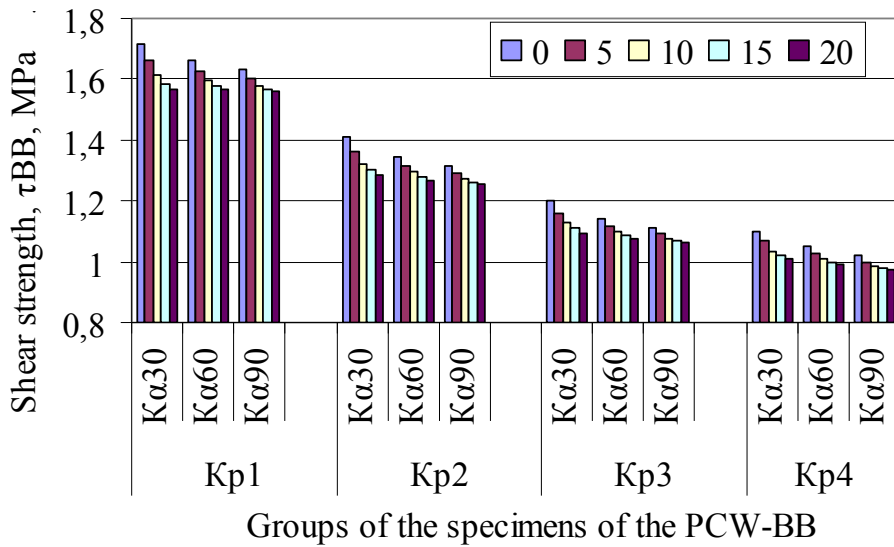


Fig. 18. The results of the PCW BB shear strength (K_p – the thickness-to-width ratio of the strip; K_α – the slope of annual rings of strips; K_N – PCW age (the lifetime of the product))

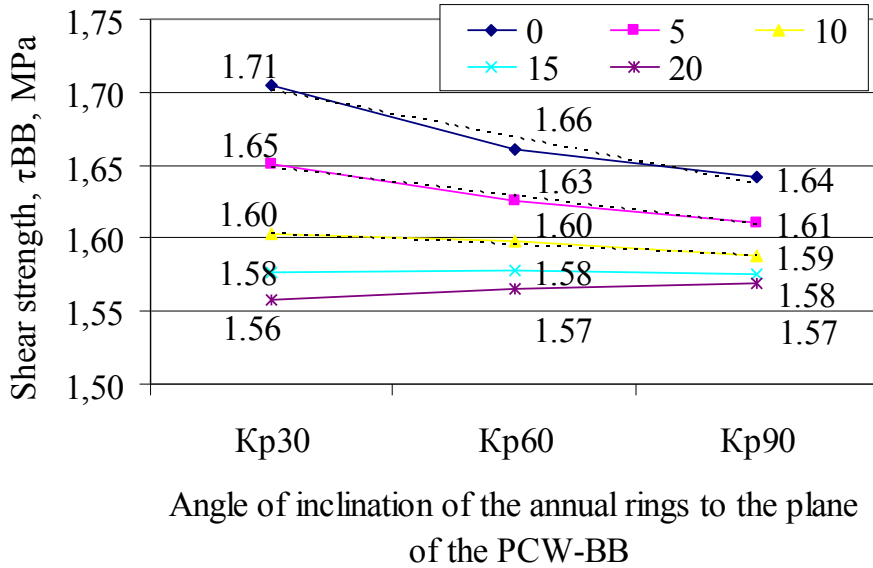


Fig. 19. Graphic dependencies $\tau_{BB} = f(K_\alpha, K_N)$ at the cross section of the strip 16×16 (K_{p1})

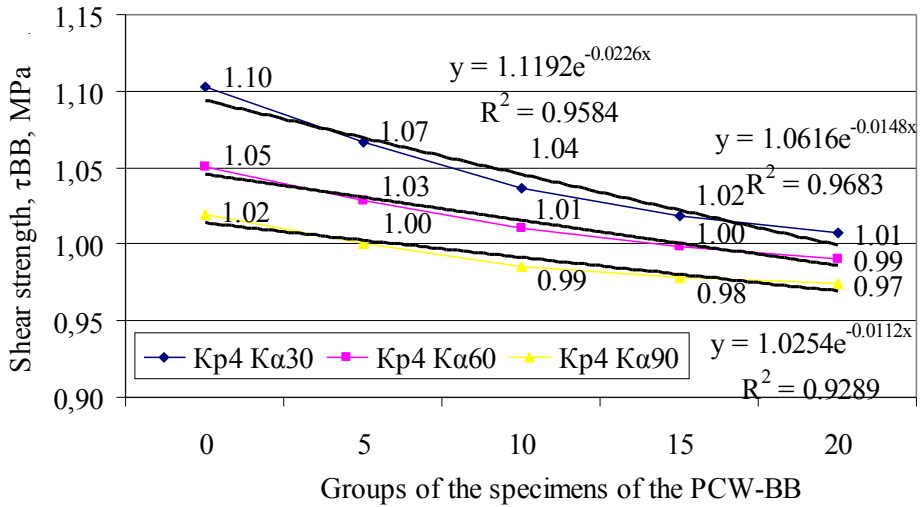


Fig. 20. Graphic dependencies $\tau_{BB} = f(K_\alpha, K_N)$ at the cross section of the strip 64×16 (K_{p4})

Comparison and discussion of results

Comparative analysis of strength values in static bending

In the process of research and data processing, a comparative analysis of both theoretical and experimental studies of the physico-mechanical characteristics of the PCW-made blockboards was performed, namely, a comparative analysis of the strength values of the PCW-made blockboards in static bending obtained by the mathematical model and by experiment for strips with a cross section of 16×16 mm (K_1) of different ages (K_N) and different angles of the annual rings slope to the blockboard face (K_p), (table 4), a comparative analysis of static bending strength values obtained by the mathematical model and by experiment for strips with a cross section of 64×16 mm (K_4) (Table 5).

Table 4. Comparative analysis of the bending strength of the PCW-BB for K_{p1}

PCW age	Mathematical model results			Experiment results		
	$K_{\alpha 30}$	$K_{\alpha 60}$	$K_{\alpha 90}$	$K_{\alpha 30}$	$K_{\alpha 60}$	$K_{\alpha 90}$
0	23.25	27.15	31.70	22.58	27.05	31.32
5	22.87	26.69	31.15	22.31	26.32	30.38
10	22.50	26.26	30.63	22.07	25.76	29.65
15	22.14	25.84	30.12	21.99	25.46	29.23
20	21.79	25.44	29.63	21.81	25.16	28.83

Table 5. Comparative analysis of the bending strength of the PCW-BB for K_{p4}

PCW age	Mathematical model results			Experiment results		
	$K_{\alpha 30}$	$K_{\alpha 60}$	$K_{\alpha 90}$	$K_{\alpha 30}$	$K_{\alpha 60}$	$K_{\alpha 90}$
0	16.47	19.23	22.45	15.05	19.84	22.17
5	16.20	18.91	22.06	14.87	19.30	21.51
10	15.94	18.60	21.69	14.71	18.89	20.99
15	15.68	18.30	21.33	14.66	18.67	20.69
20	15.43	18.01	20.98	14.54	18.45	20.41

The largest deviations of the experimental data on conventional PCW blockboards for K_{p1} and K_{p4} from the model data are insignificant. The deviation of the experimental data from the model for strips with a cross section of 16×16 mm (K_1) data for the angles of the annual rings slope to the blockboard face for $K_{\alpha 30}$ was 1-3%, $K_{\alpha 60}$ – 1-2%, and $K_{\alpha 90}$ – 1-3% (Fig. 21).

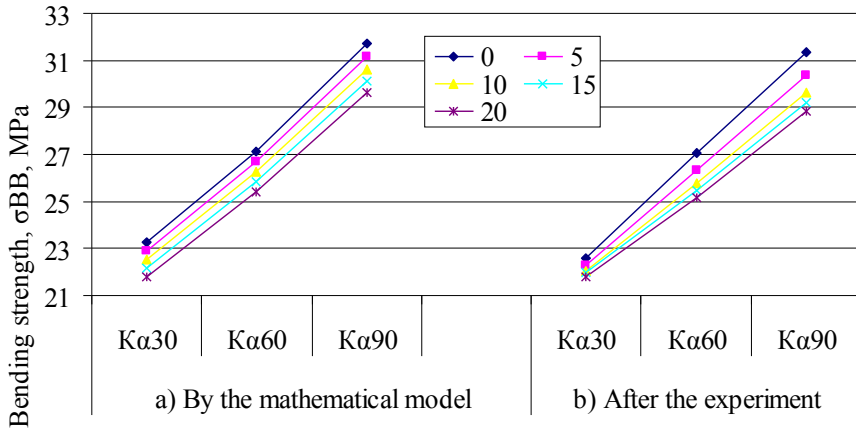


Fig. 21. Graphical comparative analysis of the results of the PCW-BB bending strength with model and experiment for K_{p1} strips of different ages

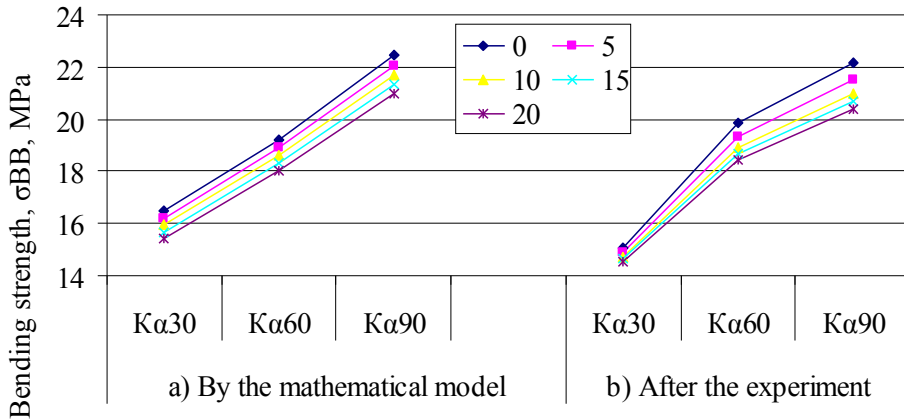


Fig. 22. Graphical comparative analysis of the results of the PCW BB bending strength with model and experiment for K_{p4} strips of different ages

The deviation of the experimental data from the model for strips with a cross section of 64×16 mm (K_{p4}) data for the angles of the annual rings slope to the blockboard face for $K_{\alpha30}$ was 6-8%, $K_{\alpha60}$ – 2-3%, and $K_{\alpha90}$ – 1-3% (Fig. 22). The model for static bending and influence of factors to be equivalent to the experimental data.

Comparative analysis of shear strength values

Comparative analysis of shear strength values obtained by the mathematical model and by experiment for strips with a cross section of 16×16 mm (K_1) (Table 6): The deviation of the experimental data from the model data for the

angles of the annual rings slope to the blockboard face for $K_{\alpha 30}$ was 6-9%, $K_{\alpha 60}$ – 3-5%, and $K_{\alpha 90}$ – 1-2% (Fig. 23).

Table 6. Comparative analysis of the shear strength of the PCW-BB for K_{p1}

PCW age	Mathematical model results			Experiment results		
	$K_{\alpha 30}$	$K_{\alpha 60}$	$K_{\alpha 90}$	$K_{\alpha 30}$	$K_{\alpha 60}$	$K_{\alpha 90}$
0	1.57	1.61	1.66	1.71	1.66	1.64
5	1.54	1.58	1.62	1.65	1.63	1.61
10	1.51	1.55	1.59	1.60	1.60	1.59
15	1.48	1.52	1.56	1.58	1.58	1.58
20	1.45	1.49	1.53	1.56	1.57	1.57

Comparative analysis of shear strength values obtained by the mathematical model and by experiment for strips with a cross section of 64×16 mm (K_4) (Table 7): The deviation of the experimental data from the model data for the angles of the annual rings to the blockboard face amounted to 7-10% for $K_{\alpha 30}$, $K_{\alpha 60}$ – 2-4%, and $K_{\alpha 90}$ – 1-4% (Fig. 24).

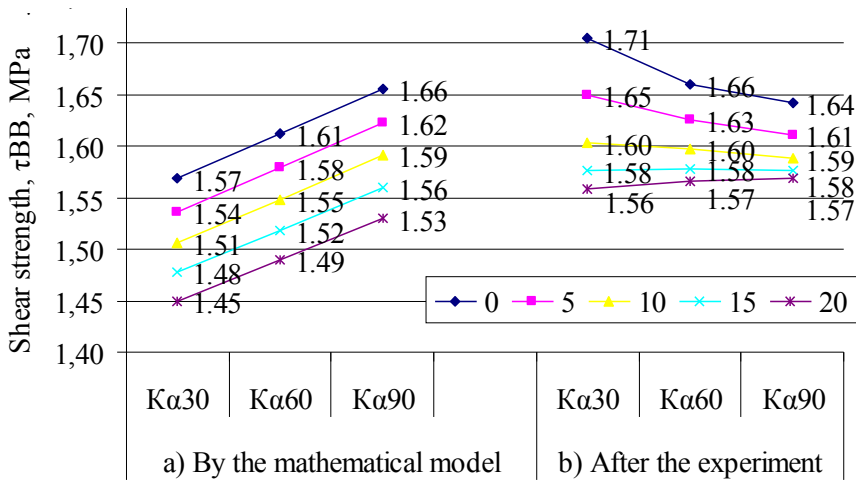


Fig. 23. Graphical comparative analysis of the results of the PCW-BB shear strength with model and experiment for K_{p1} strips of different ages

The shear strength model is completely equivalent for factors such as the ratio of the cross-sectional dimensions of the strips K_p and the age of the PCW K_N , but it is only partially equivalent for the factor such as the angle of annual rings slope to the blockboard face K_α for strips K_{p1} , and for other strips, the trend of the lines was slightly changed, which is associated with an insignificant error

in experimental studies, in particular, when measuring the angles of the annual rings slope to the blockboard face, this is especially true for wide strips.

Table 7. Comparative analysis of the shear strength of the PCW-BB for K_{p4}

PCW age	Mathematical model results			Experiment results		
	$K_{\alpha30}$	$K_{\alpha60}$	$K_{\alpha90}$	$K_{\alpha30}$	$K_{\alpha60}$	$K_{\alpha90}$
0	1.00	1.03	1.06	1.10	1.05	1.02
5	0.98	1.01	1.04	1.07	1.03	1.00
10	0.96	0.99	1.02	1.04	1.01	0.99
15	0.95	0.97	1.00	1.02	1.00	0.98
20	0.93	0.95	0.98	1.01	0.99	0.97

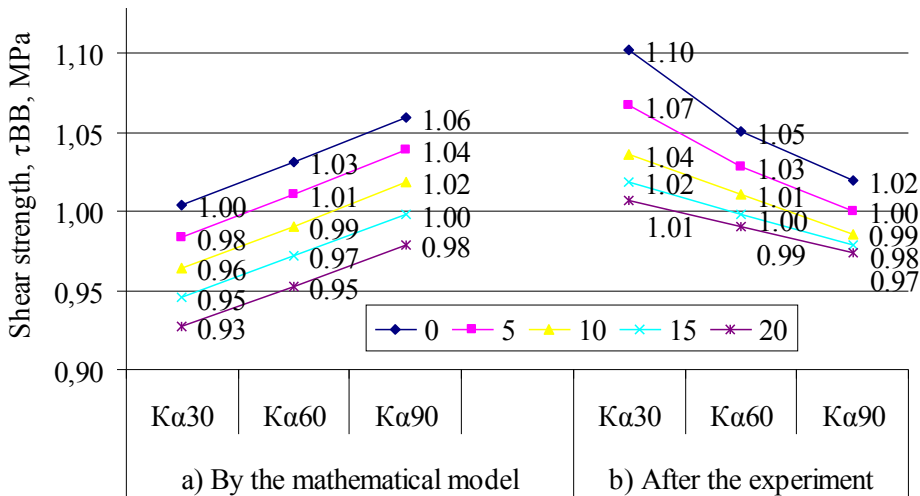


Fig. 24. Graphical comparative analysis of the results of the PCW-BB shear strength with model and experiment for K_{p4} strips of different ages

Conclusions

1. It is proved that PCW is suitable as a secondary resource for use in woodworking industry: the manufacture of structural materials, in particular, the blockboards (BBs) with predictable characteristics.
2. New designs have been developed for a conventional PCW- blockboards with glued strips having a unified size ratio of the sides of the cross section 1:1, 2:1, 3:1 and 4:1. In the designs of conventional PCW blockboards the use of strips with different angles of the annual rings slope to the face is possible on condition of their properly laying.
3. Mathematical models have been developed for predicting the main characteristics of conventional PCW-made blockboards: strength under static

bending across strips, σ_{BB} , shearing strength along the glue line, τ_{BB} , the implementation of which will facilitate the selection of rational designs of PCW-made blockboards.

4. Identified were the patterns of the influence of the structural elements properties on the characteristics of conventional PCW-made blockboards ($500 \times 500 \times 22$ mm). It was found that increasing the width of the strips leads to a decrease in strength (by 29-37%); an increase in the angle of the annual rings slope to the BB face leads to an increase in static bending strength (by 31-33%) but to a decrease in shearing strength (by 4-7%); an increase in the age of PCW leads to a decrease in strength values (by 3-8%).

5. It was found that the deviations of the values obtained by mathematical models for determining the strength in static bending of conventional PCW blockboards, compared to the experimental data did not exceed 8%. The model for in static bending and influence of factors to be equivalent to the experimental data.

6. It was found that the deviations of the values obtained by mathematical models for determining the strength in shearing of conventional PCW blockboards, compared to the experimental data did not exceed 10%. The shear strength model is completely equivalent for factors such as the ratio of the cross-sectional dimensions of the strips K_p and the age of the PCW K_N , but it is only partially equivalent for the factor such as the angle of annual rings slope to the blockboard face K_α for strips K_{p1} , and for other strips, the trend of the lines was slightly changed, which is associated with an insignificant error in experimental studies, in particular, when measuring the angles of the annual rings slope to the blockboard face, this is especially true for wide strips.

7. The obtained patterns of the effect of the width of BB strips made from PCW solid on the static bending strength and the shearing strength allow establishing rational schemes for laying strips, applying the optimal size ratio in the sides of the cross section of strips for blockboard structures.

8. It was found that the highest index of strength in static bending (31.32 MPa at a rate of 15 MPa) is characteristic of PCW-BB of the following structures: the ratio of the cross-sectional dimensions of the strips K_{p1} (1:1) with the annual rings slope to the blockboard face $K_{\alpha1}$ (61-90°), at the age of the PCW K_{N1} (0), and the lowest (14.54 MPa) – at K_{p4} (4:1) with the annual rings slope to the blockboard face $K_{\alpha3}$ (1-30°), at the age of the PCW K_{N5} (16-20). This indicates that the radial strips in the blockboard structure offer greater resistance to destruction than tangential ones.

9. It was found that the highest index of shear strength along the glue line (1.71 MPa at a rate of 1 MPa) is characteristic of PCW-BB of the following design: the cross-sectional dimensions of the strips K_{p1} (1:1) with the annual rings slope to the blockboard face $K_{\alpha3}$ (1-30°) at the age of the PCW K_{N1} (0), and the lowest

index (0.97 MPa) at K_{p4} (4:1) with the annual rings slope to the blockboard face K_{a1} (61-90°), at the age of the PCW K_{N5} (16-20). It can be seen that the tangential strips adhere better (have greater adhesion) to the facing than the radial ones.

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List of standards

- DIN EN 326-1:1994** Wood-based panels. Sampling, cutting and inspection. Sampling and cutting of test pieces and expression of test results
- DIN 68705-2:2016-03** Plywood – Part 2: Blockboard and laminboard for general use
- GOST 9620:1994** Laminated glued wood. Sampling and general requirements in testing
- GOST 9624:2009** Laminated glued wood. Method for determination of shear strength
- GOST 9625:2013** Laminated glued wood. Methods for determination of ultimate and modulus of elasticity in static bending
- GOST 13715:1978** Glued boards. Specifications
- GOST 28840:1990** Machines for tension, compression and bending testing of materials. General technical requirements
- ISO 13609-2014** Wood-based panels - Plywood - Blockboards and battenboards
- ISO 12579-2007** Timber structures – Glued laminated timber – Method of test for shear strength of glue lines
- PN-76/D-97000** Plyty stolarskie (Blockboards)
- PN-EN 310:1994** Wood-based panels. Determination of modulus of elasticity in bending and of bending strength

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