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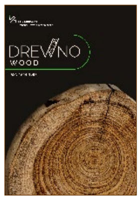

Study of Physical and Mechanical Properties of Post-Consumer Wood of Different Age

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It should be noted that there is currently a problem with wood resources in the woodworking industry. A potential, unused wood reserve is post-consumer wood (PCW). The problem with the quality of this wood resource has not been fully resolved since there is no regulatory database. In fact, there is a lack of appropriate regulatory documents, which makes it impossible to describe to a full extent the physical and mechanical properties of PCW of common wood species of different ages as a source of additional raw materials for various woodworking technologies. Proceeding from the goal, the task of the study is to describe the physical and mechanical properties of post-consumer wood using the example of fir wood, which for a long period of time has been used to create furniture and joinery products. The task is also to identify patterns of change in the indicators of this resource with age – an expired service life or suitability.

In order to use PCW in woodworking and to fill the scientific base with physical and mechanical indicators of fir wood of different ages with an expired product service life, the following characteristics were investigated: static hardness, swelling, coefficients of swelling, the value of transverse anisotropy, density, static bending strength, splitting strength along the fibers, modulus of elasticity in compression, and the modulus of elasticity in static bending. The characteristics of PCW of the widespread fir species in the range of use from 0 to 20 years were explored, with intermediate control over the properties every 5 years.

The dynamics of the physical and mechanical indicators of fir PCW were revealed and it was found that in the course of operation time in various conditions they change, mainly decreasingly: static hardness by 9.2-9.6%; the value of transverse anisotropy by 30-32%; strength: static bending strength by 3.4-7.95%, splitting strength by 4.49-8.67%; modulus of elasticity: in compression by 3.89-4.08%, in bending by 2.75-6.64%. The main causes of changes in the properties of PCW with age: natural: weathering, partial internal rot, insect damage, other biological effects; mechanical: splitting, scratches, small holes from means of fastening and other defects due to use; operational: the influence of power and dynamic loads, the influence of surface finishing agents and other factors on the structural elements of wood products. A summary table was compiled for the selection of indicators of the physical and mechanical properties of fir PCW of different ages. When knowing the indicators and dynamics of the physical and mechanical properties of PCW with age, it can be recommended for manufacturing structural materials – blockboards and furniture panels.

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Introduction

The problem of the accumulation and utilization of used wood became especially pressing at the beginning of the 21st century, which is associated with the development of processing industries. This is indicated in the scientific works of researchers from different countries Gayda [2007, 2010, 2011a, 2011b, 2013, 2015a, 2015b, 2016, 2017a, 2017b, 2018], Gayda & Lesiv [2019], Gayda & Kiyko [2020a, 2020b], Mantau, Wagner, Baumann [2005], Marutzky [2003], Ratajczak et al. [2018].

According to the European project COST Action E31 [2007], PCW is a real and additional raw material that must be processed and re-involved in economic activities as a raw-material and energy resource. On March 1, 2003, the European Union adopted the normative document "AltholzV" [2003], which on the one hand, prohibits the accumulation of used wood in landfills, the disposal of ecologically questionable and harmful resources to landfills, and on the other hand, obliges the manufacturers of wood products to specify ways of recycling products with an expired service life or suitability. The accumulation of PCW in landfills is very harmful to the environment due to the content of harmful substances, which is noted in the works of researchers such as Boehme [2003], Grigoriou [1996], Erbreich [2004], Lykidis & Grigoriou [2005], Werner et al. [2007].

Ratajczak E. [2013] and other Polish researchers such as Wroblewska H., Cichy W. [1997] describe possible ways of using PCW, discussing a cascade model of treatment of this raw material – the step-by-step processing of the resource into suitable wooden products; if it is not effective, only then should incineration be carried out. Marutzky R. [2003] described the methods of processing PCW into chipboards. However, the above-mentioned researchers did not provide information on the effective use of PCW in its entirety, that is, dimensionally suitable blanks with high-quality indicators.

Regarding another aspect, wood as the main raw material for the manufacture of wood products has been under constant study by a wide range of researchers who have studied it from various aspects: its structure, physical and mechanical properties. Widely known are the works of researchers such as Ugolev [2011], Borovikov [1989], Sopushynsky [2012], Vintoniv, Sopushinsky, Sopushinska [2004], Ashkenazi [1980] and others, who conducted studies in major areas such as the micro- and macrostructure of wood, physical and mechanical properties, technological and rheological properties, impregnation and the protection of wood. All these studies dealt with primary wood, not PCW which was in operation for 10, 20 or more years. In other words, there is a problem of indicators, that is, the physical and mechanical properties of PCW, especially of different ages, and this problem has not been resolved.

The works by Tsybyk [1963] deal with the structure as well as physical and mechanical properties of coniferous species wood of the Ukrainian Carpathians (silver fir, Norway spruce, Scots pine, Douglas-fir, yew), depending on the type of forest growth conditions. Some scientists studied in detail the properties of the wood of particular species: Vintoniv., Sopushinsky, Taishinger (sycamore) [2007], Maksymchuk (silver fir) [2017]. Other researchers investigated only certain properties of wood: Poluboyarynov (density) [1976], Ashkenazi (anisotropy) [1980], Ugolev (wood deformity) [2011], Vintonov., Sopushinsky, Sopushinska [2004] (decorative properties) [2004], Maksymchuk (swelling) [2017] and others. Nonethless, there is one thing in common: all of their studies were concerned with primary wood.

To date, there have been no scientific studies on the physical and mechanical properties of post-consumer wood (used wood), that is, wood that has already been exploited in various conditions and could change its properties over time. Furthermore, this complicates its further material use, in particular for the production of blockboards.

Knowledge of the dynamics of changes in the physical and mechanical properties of used wood with age is an urgent problem for research. After all, knowing the properties of PCW of different ages, one can recommend it for the manufacture of certain products, as well as to predict the characteristics of new products.

Problem. Research goal and output measures

The problem is the lack of normative documents which indicate the physical and mechanical properties of PCW of different species of wood of different ages as a source of additional raw materials for different woodworking technologies. The solution to the problem of using PCW in woodworking technologies would be impossible without studying the physical and mechanical properties of PCW of different ages of the main tree species that were operated in different conditions. The study and analysis of the main indicators of PCW is an urgent task, the solution of which will ensure the manufacture of high-quality wood products with maximum consideration of the physical and mechanical properties of secondary-use materials.

The aim of the studies is to establish the dynamics of changes in the physical and mechanical properties of the used wood as in the case of fir with age – during its operation in the structures of wood products.

Ultimately, the results of the experiments are necessary in the study of predicting the properties of products from PCW.

To achieve this goal, it is necessary to solve the following tasks:

- to review and analyze the current state of the problem
- to experimentally investigate the physical and mechanical properties of used wood
- to establish patterns of changes in indicators of this resource with age.

Among the range of physical and mechanical parameters of wood, the most characteristic and necessary indicators that are important for the use of PCW in the production of structural materials, in particular blockboards, were identified for further examination. They include indicators will be used for:

Determination of the characteristics of blanks from PCW for blockboards:

- density – ρ_o, ρ_8, ρ_{30}, kg/m^3
- static hardness – H, MPa
- maximum swelling – α_t, α_r, α_l, α_v, %
- coefficients of swelling – K_t , K_r , K_l , K_v
- the value of transverse anisotropy – $K_{an} = \alpha_t / \alpha_r$.

Determination of the characteristics of blockboards from PCW:

- splitting strength along the fibers – τ_{1-30}, τ_{31-60}, τ_{61-90}, MPa
- static bending strength – σ_{1-30} , σ_{31-60}, σ_{61-90}, MPa.

Prediction of the characteristics of blockboards from PCW:

- modulus of elasticity in static bending – E_{1-30}, E_{31-60}, E_{61-90}, MPa
- modulus of elasticity in compression – E_α , E_r , E_t, MPa.

Materials and methods

For the experiments, PCW of different origin and four groups of different ages of operation was used: packing (containers, pallets, boxes), wood from the demolition and dismantling of buildings (elements of wall constructions and frameworks of roofs), frames of furniture products (chairs and tables), elements of millwork (window and door units).

The properties of PCW of different ages of species such as fir were investigated and a comparative analysis of the properties of PCW was carried out according to the current standards, which made it possible to compare its properties with those of primary wood. Fir wood is widely used in the woodworking industry, but it is poorly studied in comparison with other species.

Methods of preparing test specimens

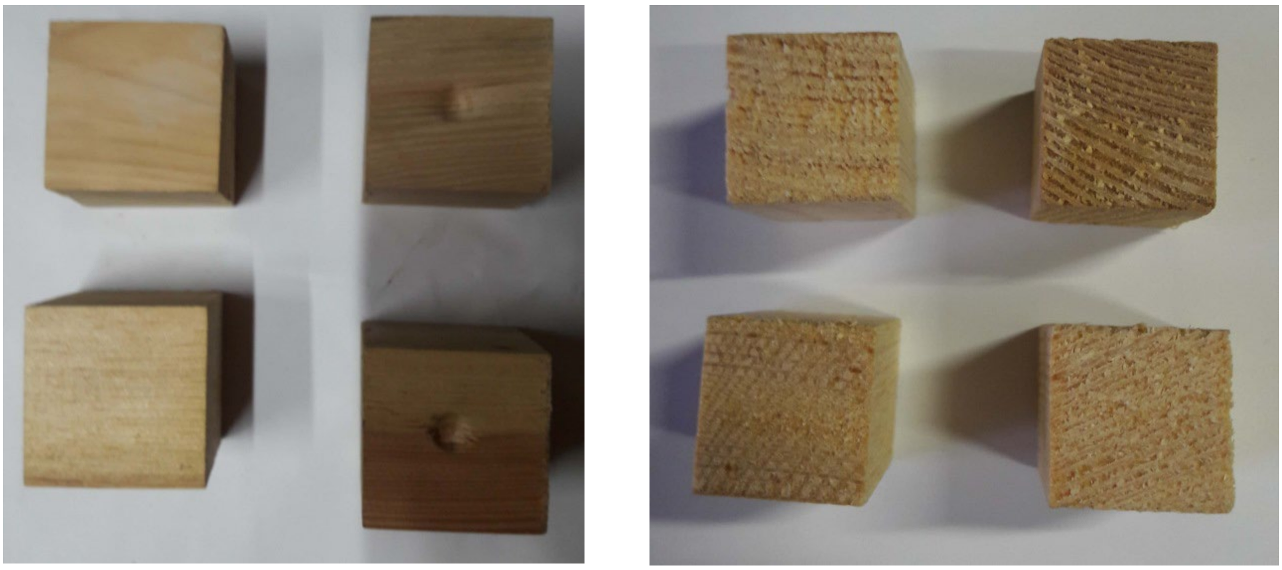
Strips (Fig. 1) of appropriate cross-sections were prepared for the study, from which specimens for the experiments were made [EN 350-2:2004, EN 460:2018, ISO 3129:2019].

Fig. 1. Strips for specimens

The strips were conditioned at room temperature (Fig. 2).

Fig. 2. Strips kept at room temperature

Specimens of the required sizes were made from the long strips (Fig. 3)



a) for static hardness tests

b) for static bending strength and modulus of elasticity in static bending tests

c) for density and swelling tests

Fig. 3. Types of specimens for testing

Fig. 4. Assortment of specimens for testing

Dimensions of the prepared specimens for testing:
– density and swelling – 30 × 20 × 20 mm
– static hardness – 50 × 50 × 50 mm
– static bending strength – 300 × 20 × 20 mm
– modulus of elasticity in static bending – 300 × 20 × 20 mm
– splitting strength along the fibers – 50 × 30 × 20 mm
– modulus of elasticity in compression – 60 × 20 × 20 mm.

Types of experimental tests – methods of experimental research

Nowadays, there is a series of GOST standards of different years of publication which provide a methodology for performing various studies on wood. Also, during the study of the physical and mechanical, as well as technological indicators of coniferous species, the current standards of Ukraine are used, developed on the basis of European regulatory documents.

Research methods: testing of the experimental specimens – to determine the properties of PCW; mathematical statistics – for processing the results of the experimental studies. All the tests were performed in a laboratory at a temperature of 20±5°C, at a relative air humidity of 40-65%. The prepared PCW specimens were tested on the equipment of GOST 28840:1990, according to the known techniques (methods of definition) provided by the standards.

The static hardness (H_W) was calculated according to GOST 16483.17:1981 «Wood. Method for determination of static hardness» by the formula:

$$H_W = \frac{P_{max}}{F} = \frac{P_{max}}{\pi \cdot r^2}, \text{ MPa}, \quad (1)$$

where: P_{max} – maximum load, H; F – projection area of the imprint, F = 100 mm^2, r – radius of the hemisphere of the punch, r = 5.64 mm.

Swelling was calculated according to GOST 16483.35:1988. «Wood. Method for determination of swelling».

Maximum swelling α_{max} was determined for different directions and by the formulas:

$$\alpha_{r\max} = \frac{(L_{r\max} - L_{r\min})}{L_{r\min}} \cdot 100 \text{ and } \alpha_{t\max} = \frac{(L_{t\max} - L_{t\min})}{L_{t\min}} \cdot 100, \quad (2)$$

where: L_{max} – maximum size of the sample at the humidity of 30%, L_{min} – minimum size of the sample in a completely dry state.

The coefficient of swelling K_α was determined for different directions and by the formulas:

$$K_{\alpha r} = \frac{\alpha_{r\max}}{W_n} \text{ and } K_{\alpha t} = \frac{\alpha_{t\max}}{W_n}, \quad (3)$$

where: W_n – saturation limit of the cell walls of wood, 30%

The density (ρ_W) was calculated according to GOST 16483.1:1984 «Wood. Method for determination of density» by the formula:

$$\rho_W = \frac{m_W}{a_W \cdot b_W \cdot l_W}, \text{kg/m}^3, \quad (4)$$

where: m_W – mass of the sample at the humidity of W, kg; a_W, b_W, l_W – sample size at humidity W, m.

The static bending strength (σ_W) was calculated according to GOST 16483.3:1984. «Wood. Method of static bending strength determination» by the formula:

$$\sigma_W = \frac{P_{\max} \cdot l}{2b \cdot h^2}, \text{ MPa}, \quad (5)$$

where: P_{max} – maximum load, H; l – distance between the centers of the supports, mm; h – height of the sample, mm; b – width of the sample, mm.

The ultimate splitting strength along the fibers (τ_W) was calculated according to GOST 16483.5:1973. «Wood. Methods for determination of ultimate splitting strength along the fibers» by the formula:

$$\tau_W = \frac{P_{\max}}{b \cdot l}, \text{ MPa}, \quad (6)$$

where: P_{max} – maximum load, H; b – thickness of the sample, mm; l – chipping length, mm.

The modulus of elasticity in static bending (E_W) was calculated according to GOST 16483.9:1973. «Wood. Methods for determination of modulus of elasticity in static bending» by the formula:

$$E_W = \frac{3P \cdot l^3}{64b \cdot h^3 \cdot f}, \text{ MPa}, \quad (7)$$

where: P – load equal to the difference between the upper and lower limits of the load, H; l – distance between the supports, mm; b – width of the sample, mm; h – height of the sample, mm; f – deflection of the sample in the zone of pure bending, equal to the difference between the arithmetic mean of the measurement of deflection at the upper and lower limits of the load, mm.

The modulus of elasticity in compression along the fibers (E_W) was calculated according to GOST 16483.24:1973. «Wood. Determination method of modulus of elasticity in compression along the fibers» by the formula:

$$E_W = \frac{P \cdot l}{F \cdot \Delta l} = \frac{P}{F \cdot \varepsilon} = \frac{\sigma}{\varepsilon}, \text{ MPa}, \quad (8)$$

where: P – load equal to the difference between the upper and lower limits of the load, H; ε – relative deformation; σ – voltage, MPa; l – initial size of the sample (layer), mm; Δl – size increase (difference between final and initial length), mm; F – cross-sectional area, m^2.

Methods of processing research results

Statistical processing of the results of the study of the physical and mechanical properties of the used wood was performed using the *Excel* program. The main indicators of statistical analysis of the study results included: the sample size (the number of measurements performed), *n;* minimum value, M_{min}; maximum value, M_{max}; arithmetic mean value, $\overline{M}$; arithmetic mean error, ± *m;* sample variance, σ^2; arithmetic mean deviation of the sample, *S;* coefficient of variation, *V;* the accuracy of the experiment, *P*. The arithmetic mean value $\overline{M}$ for non-grouped values, which are determined on a sufficient and homogeneous statistical material, was found by the formula:

$$\overline{M} = \frac{M_1 + M_2 + M_3 + \ldots + M_n}{n} = \frac{\sum_{i=1}^{n} M_i}{n}, \quad (9)$$

where: $\overline{M}$ – arithmetic mean of the sample; M_i – result of a separate (first) test; *n* – sample size (number of measurements performed).

The variance of the experimental values of the sample σ^2 was found by the formula:

$$\sigma^2 = \frac{\sum_{i=1}^{n}\left(M_i - \overline{M}\right)^2}{n-1}. \quad (10)$$

The arithmetic mean deviation of the sample S was found by the formula:

$$S = \sqrt{\frac{\sum_{i=1}^{n}\left(M_i - \overline{M}\right)^2}{n-1}}. \quad (11)$$

The coefficient of variation of the sample V in percent was determined by the formula:

$$V = \frac{S}{\overline{M}}100\%. \quad (12)$$

The error of the arithmetic mean of the sample ±m was determined by the formula:

$$m = \frac{S}{\sqrt{n}}. \quad (13)$$

The indicator of the accuracy of the mean value of the sample (experiment) P was determined by the formula:

$$P = \frac{V}{\sqrt{n}}. \quad (14)$$

The measurement index based on the results of statistical processing was recorded as the arithmetic mean value and its error $\overline{M}$ ±m.

Results and discussion

Results of experimental test

Determination of static hardness of fir PCW

Determination of the static hardness of the fir specimens of different age categories by service life is presented in Figs. 5 and 6.

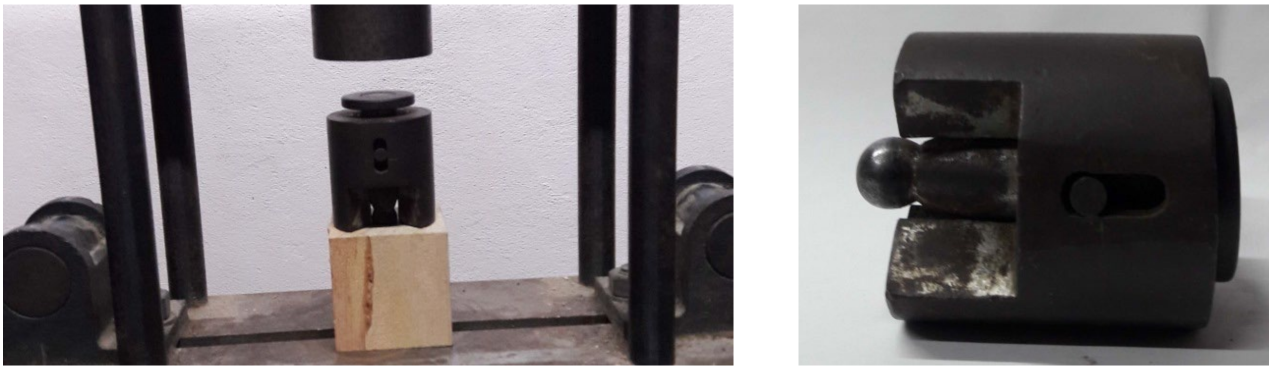


Fig. 5. Conducting experiment on static hardness of fir PCW

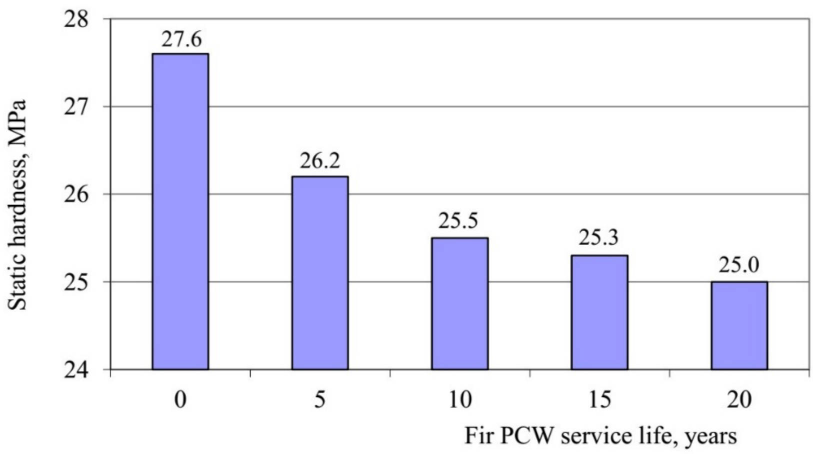


Fig. 6. Indices of static hardness of fir PCW

The results of the static hardness tests showed a decrease in the indicator for PCW (20 years) by no more than 10.00%, in particular for PCW (5) by 5.07%, for PCW (10) by 7.61%, PCW (15) by 8.34%, PCW (20) by 9.42%.

Determination of maximum swelling of fir PCW

The results of swelling of the fir wood specimens in different directions are presented in Table 1 and Figs. 7 and 8.

Table 1. Maximum swelling in specimens

Fir	Maximum swelling in directions and sizes, %			
Service life, years	in tangential direction α_t	in radial direction α_r	in length α_l	by volume α_v
0	8.90	4.50	0.57	14.45
5	7.41	4.24	0.43	12.45
10	6.26	3.98	0.33	10.85
15	5.37	3.77	0.27	9.63
20	4.89	3.62	0.20	8.91
Decrease, %	45.06	19.56	64.91	38.34

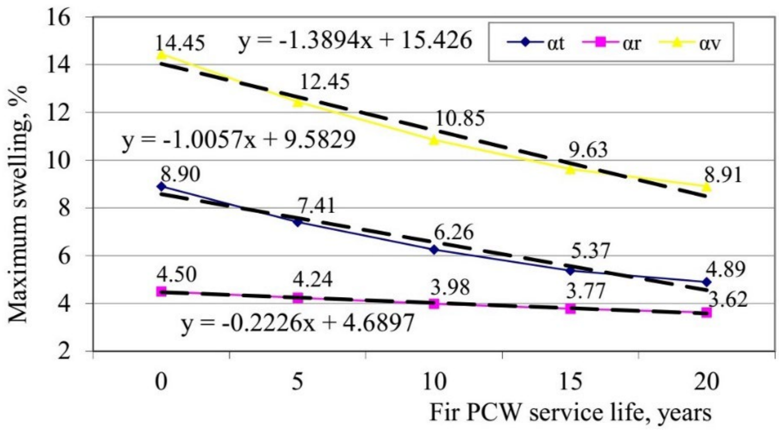


Fig. 7. Dependence of swelling in different directions on age of fir PCW

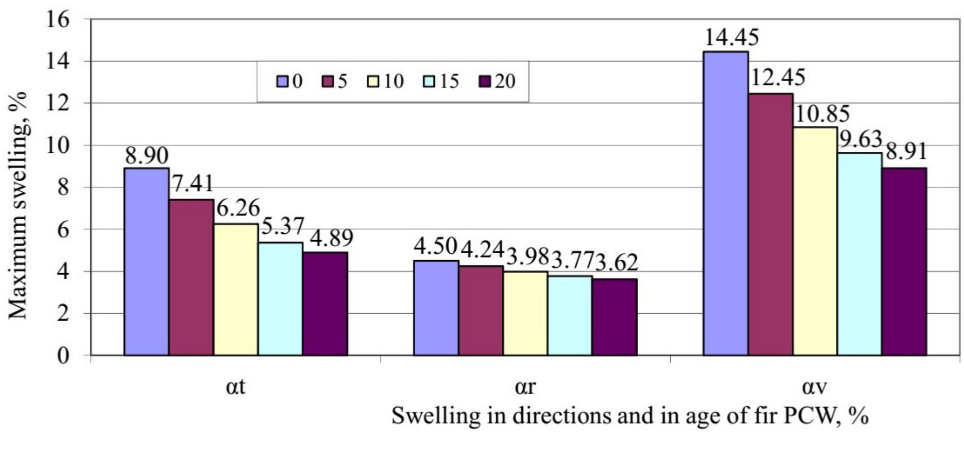


Fig. 8. Indices of swelling in different directions depending on age of fir PCW

The results of the study, in particular the volumetric maximal swelling showed a decrease in the indicator for PCW (20 years) by no more than 40.00%, in particular for PCW (5) by 13.84%, for PCW (10) by 24.91%, PCW (15) by 33.36%, PCW (20) by 38.34%.

Calculation of transverse anisotropy value of fir PCW

The results of determining the value of the transverse anisotropy of fir wood in different directions are given in Table 2 and in Fig. 9.

Table 2. Transverse anisotropy value

Fir Service life, years	Coefficients of swelling in tangential direction K_t	in radial direction K_r	in length K_l	by volume K_v	Transverse anisotropy value α_t / α_r
0	0.297	0.150	0.019	0.48	1.98
5	0.247	0.141	0.014	0.41	1.75
10	0.209	0.133	0.011	0.36	1.57
15	0.179	0.126	0.009	0.32	1.42
20	0.163	0.121	0.007	0.30	1.35
Decrease, %	45.12	19.33	63.16	37.50	31.82

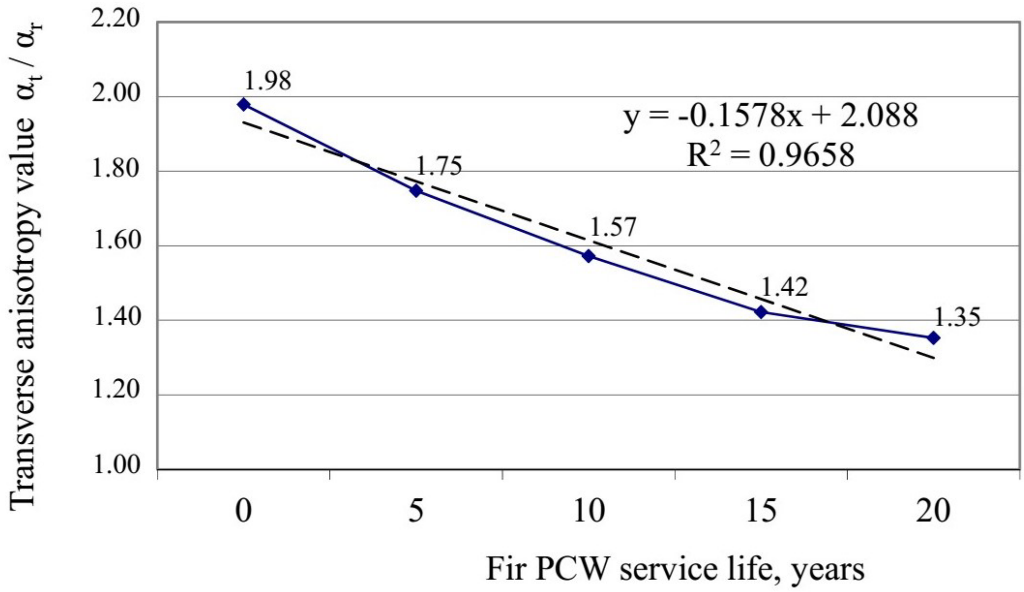


Fig. 9. Dependence of the value of transverse anisotropy on age of fir PCW

The results of the study, in particular the volume coefficient of swelling showed a decrease in the indicator for PCW (20 years) by no more than 38.00%, in particular for PCW (5) by 14.58%, for PCW (10) by 25.00%, PCW (15) by 33.33%, PCW (20) by 37.50%.

The results of the study, in particular the transverse anisotropy showed a decrease in the indicator for PCW (20 years) by no more than 32.00%, in particular for PCW (5) by 11.62%, for PCW (10) by 20.71%, PCW (15) by 28.28%, PCW (20) by 31.82%.

Change in density of fir PCW in course of service life

The results of determining the density of fir wood of different ages are given in Table 3 and in Fig. 10.

Table 3. Density change in specimens

Fir	**Density kg/m³, при**		
Service life, years	**W=0 %** $\rho_{0\%}$	**W=8 %** $\rho_{8\%}$	**W=30 %** $\rho_{30\%}$
0	402	432	470
5	388	425	453
10	374	421	448
15	368	408	442
20	362	393	437
Decrease, %	9.81	8.88	6.96

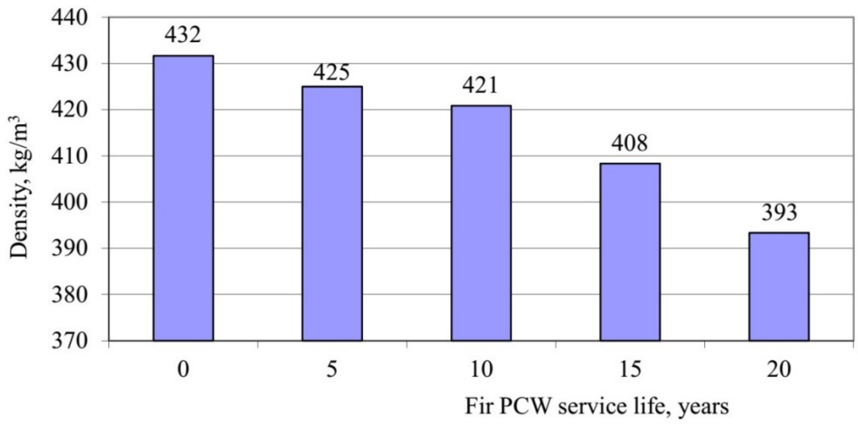


Fig. 10. Changes in density of fir wood depending on age of PCW

The results of the study, in particular the density showed a decrease in the indicator for PCW (20 years) by no more than 10.00%, in particular for PCW (5) by 1.62%, for PCW (10) by 2.55%, PCW (15) by 5.56%, PCW (20) by 9.03%.

Change in static bending strength of fir PCWwith age

The results of determining the static bending strength of fir wood of different ages are given in Table 4, in Figs. 11 and 12.

Table 4. Static bending strength in specimens (W=8 %)

Fir	**Static bending strength of fir PCW with age, MPa**		
Service life, years	**Samples by angles of inclination of annual rings to plane of blockboard.**		
	0-30º	**31-60º**	**61-90º**
0	84.67	89.26	93.96
5	83.65	86.86	91.15
10	82.76	85.01	88.94
15	82.45	84.01	87.68
20	81.79	83.01	86.49
Decrease, %	3.4	7.0	8.0

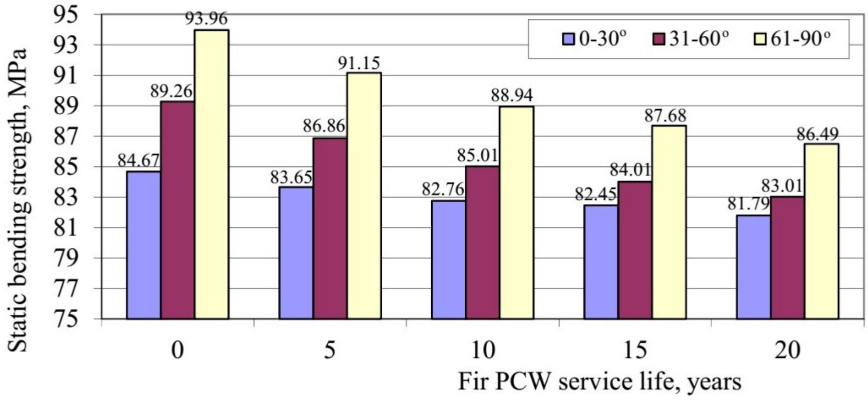


Fig. 11. Indices of static bending strength of fir PCW of different ages

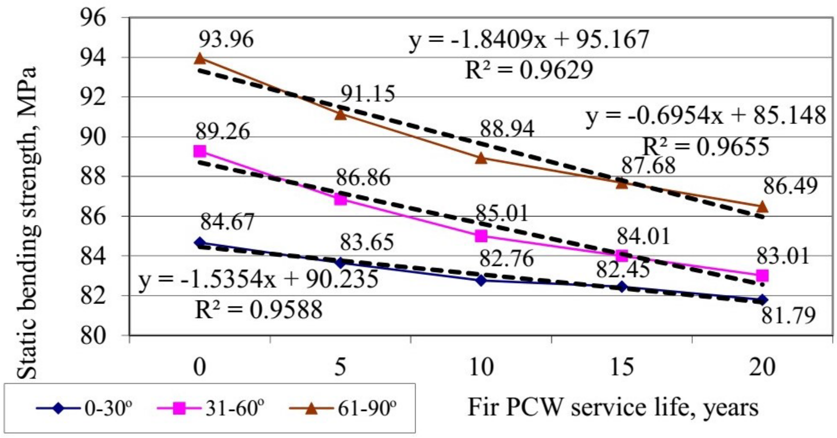


Fig. 12. Dependence of static bending strength of fir PCW on its age

The results of the study, in particular of the static bending strength, showed a decrease in the indicator for PCW (20 years) by no more than 8.00%, also, for the angles of inclination of annual rings 0-30° by 3.4%, for angles 31-60° by 7.0%, for angles 61-90° by 7.95%.

Results of splitting strength test along fibers of fir PCW with age

The results of the splitting strength test along the fibers of fir wood of different ages are given in Table 5, in Figs. 13 and 14.

Table 5. Splitting strength along fibers in specimens (W=8 %)

Fir	Splitting strength along fibers of fir PCW with age, MPa		
Service life, years	Samples by angles of inclination of annual rings to plane of blockboard		
	0-30°	31-60°	61-90°
0	8.19	7.92	7.80
5	7.92	7.75	7.65
10	7.69	7.62	7.54
15	7.57	7.53	7.49
20	7.48	7.47	7.45
Decrease, %	8.67	5.68	4.49

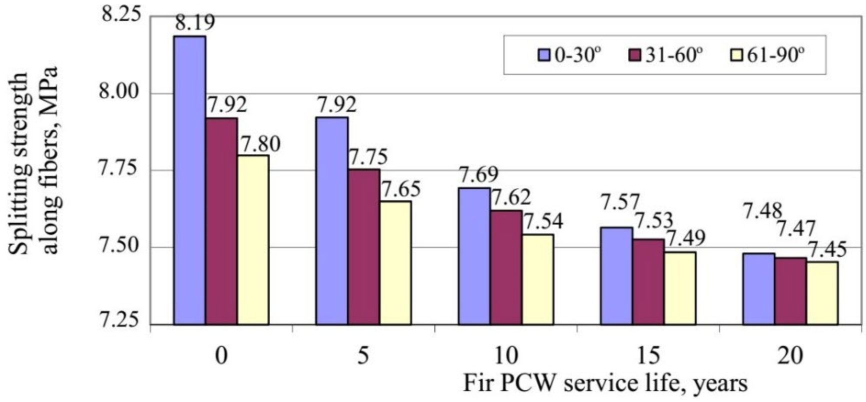


Fig. 13. Indices of splitting strength along fibers of fir PCW of different ages

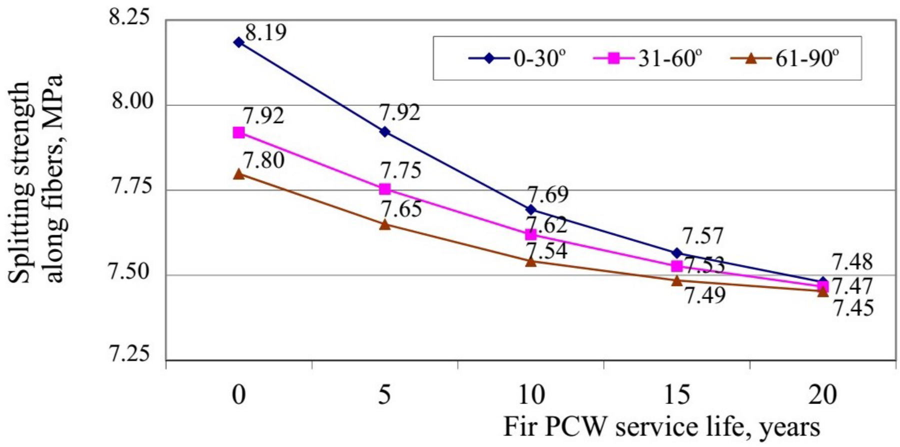


Fig. 14. Dependence of splitting strength of fir PCW on its age

The results of the study, in particular of the splitting strength, showed a decrease in the indicator for PCW (20 years) by no more than 9.00%, also, for the angles of inclination of annual rings 0-30° by 8.67%, for angles 31-60° by 5.68%, for angles 61-90° by 4.79%.

Results of modulus of elasticity test in compression of fir PCW with age

The results of the modulus of elasticity test in the compression of fir wood of different ages are given in Table 6, in Figs. 15 and 16.

Table 6. Modulus of elasticity in compression in specimens

Fir	Modulus of elasticity in compression by directions, MPa		
Service life, years	in length E_{8a}	in radial E_{8r}	in tangential E_{8t}
0	11392	739	466
5	11222	720	460
10	11111	704	455
15	11002	693	450
20	10949	685	447
Decrease, %	3.89	7.31	4.08

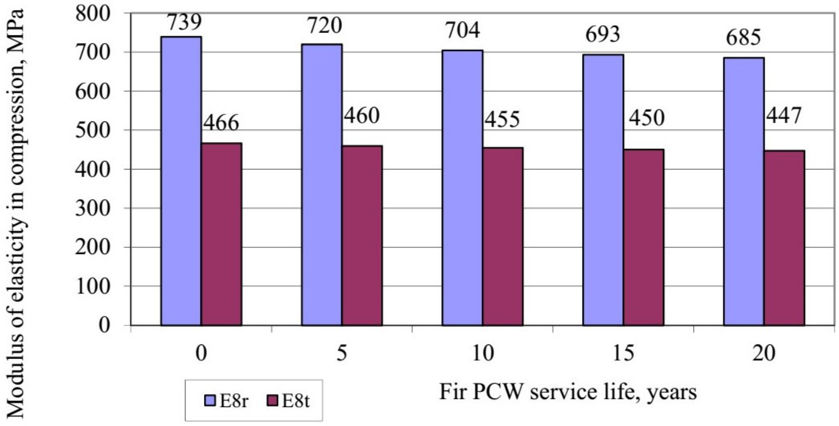


Fig. 15. Indices of modulus of elasticity in compression depending on age of fir PCW

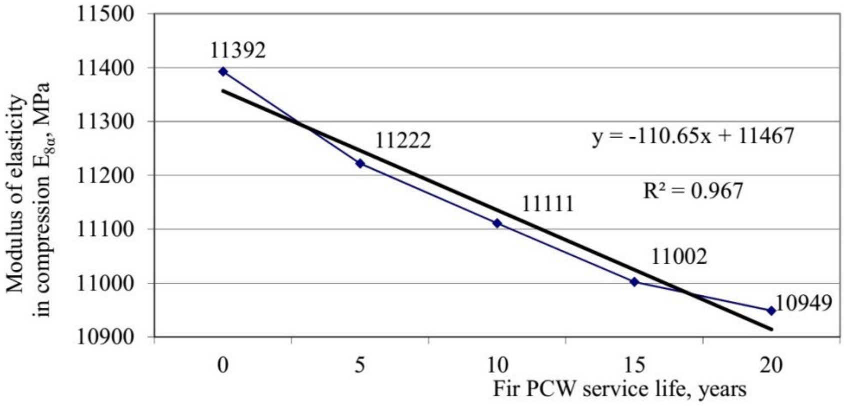


Fig. 16. Changes in modulus of elasticity in compression of fir wood depending on age of PCW

The results of the study, in particular of the modulus of elasticity in compression, showed a decrease in the value for PCW (20 years) by no more than 8.00%, in particular in the longitudinal direction by 3.89%, in the radial direction by 7.31%, in the tangential direction by 4.08%.

The dependence of the modulus of elasticity at static bending of PCW of fir on different age and inclination of annual rings.

The results of determining the modulus of elasticity in the static bending of fir wood of different ages are given in Table 7, in Figs. 17 and 18.

Table 7. Modulus of elasticity in static bending in specimens (W=8 %)

Fir	**Modulus of elasticity in static bending, MPa**		
Service life, years	**Samples by angles of inclination of annual rings to plane of blockboard**		
	0-30º	**31-60º**	**61-90º**
0	10602.09	11065.57	11440.68
5	10331.63	10887.10	11319.17
10	10125.00	10771.28	11231.28
15	9975.37	10657.89	11169.33
20	9898.35	10602.09	11126.37
Decrease, %	6.64	4.19	2.75

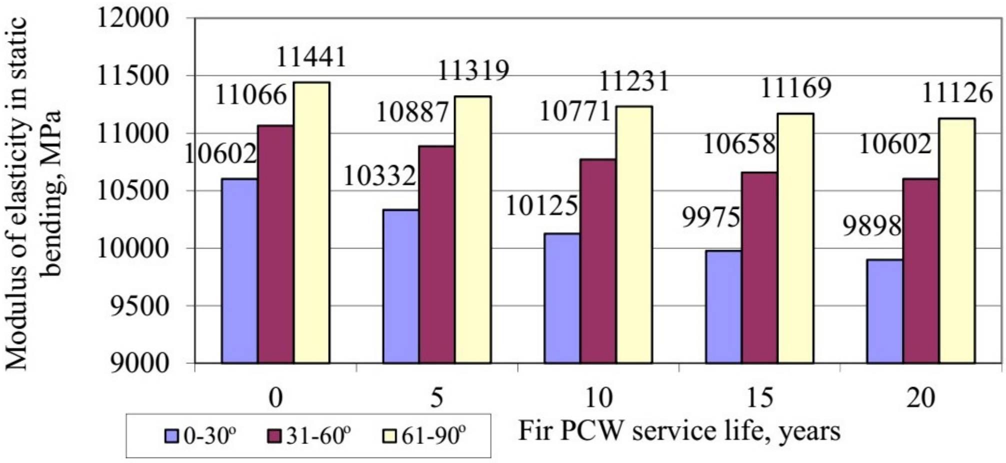


Fig. 17. Indices of modulus of elasticity at static bending of fir PCW of different ages

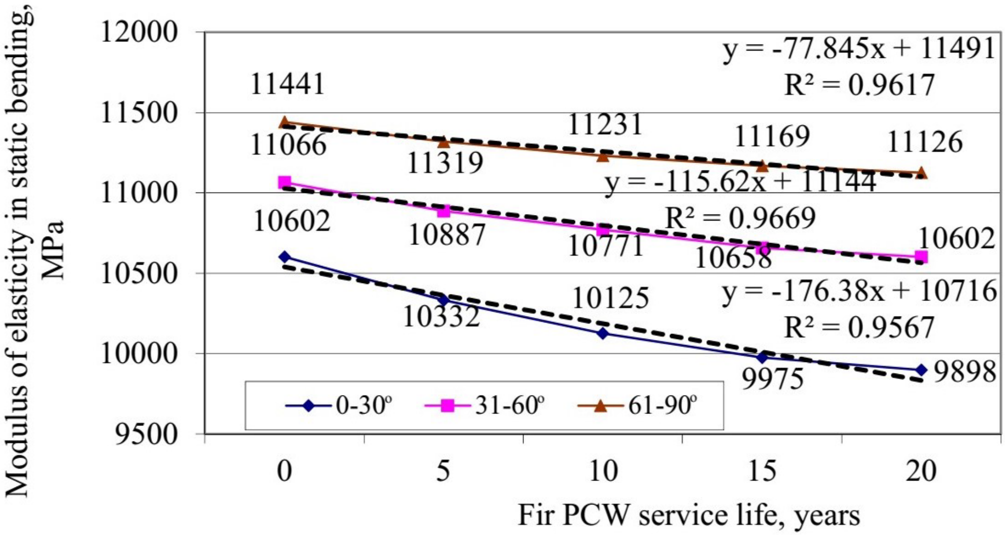


Fig. 18. Dependences of modulus of elasticity at static bending of fir PCW on age

The results of the study, in particular of the modulus of elasticity in static bending, showed a decrease in the indicator for PCW (20 years) by no more than 7.00%, also for the angles of inclination of annual rings 0-30° by 6.64%, for angles 31-60° by 4.19%, for angles 61-90° by 2.75%.

Main values of physical and mechanical properties of fir PCW of different ages and their dynamics

Thus, the characteristics of PCW of the widespread fir species in the range of use from 0 to 20 years were explored. In order to use PCW in woodworking and to fill the scientific base with the physical and mechanical indicators of fir wood of different ages with an expired product service life, the following characteristics were investigated: static hardness, maximum swelling, coefficients of swelling, the value of transverse anisotropy, density, static bending strength, splitting strength along the fibers, modulus of elasticity in compression, modulus of elasticity in static bending.

The dynamics of the studied physical and mechanical parameters of fir PCW are given in the summary Table 8.

The dynamics of the physical and mechanical indicators of fir PCW were revealed and it was found that in the course of operation time in various conditions they change, mainly decreasingly: static hardness by 9.2-9.6%; the value of transverse anisotropy by 30-32%; strength: static bending strength by 3.4-7.95%, splitting strength by 4.49-8.67%; modulus of elasticity: in compression by 3.89-4.08%, in bending by 2.75-6.64%. The main causes of changes in the properties of PCW with age: natural: weathering, partial internal rot, insect damage, other biological effects; mechanical: splitting, scratches, small holes from means of fastening and other defects from use; operational: the influence of power and dynamic loads, the influence of surface finishing agents and other factors on the structural elements of wood products.

When knowing the indicators and dynamics of the physical and mechanical properties of PCW with age, it can be recommended for manufacturing structural materials: with mechanical damage visible on the surface, and color changes for the manufacture of blockboards, with high-quality surfaces – for the manufacture of furniture panels.

The values for the indicators of the physical and mechanical properties of PCW are required for predicting the characteristics of products from wood, in particular blockboards from PCW (Table 9).

Table 8. Summarized physical and mechanical properties of fir PCW of different ages

Parameters	Symbol	PCW age					Change, %
		0	5	10	15	20	
1	2	3	4	5	6	7	8
Static hardness, MPa	H	27.6	26.2	25.5	25.3	25.0	9.42
Maximum swelling, %	α_t	8.90	7.41	6.26	5.37	4.89	45.06
	α_r	4.50	4.24	3.98	3.77	3.62	19.56
	α_l	0.57	0.43	0.33	0.27	0.20	64.91
	α_v	14.45	12.45	10.85	9.63	8.91	38.34
Coefficients of swelling	K_t	0.297	0.247	0.209	0.179	0.163	45.12
	K_r	0.150	0.141	0.133	0.126	0.121	19.33
	K_l	0.019	0.014	0.011	0.009	0.007	63.16
	K_v	0.480	0.410	0.360	0.320	0.300	37.50
Transverse anisotropy value	α_t / α_r	1.98	1.75	1.57	1.42	1.35	31.82
Density, kg/m^3	ρ_8	432	425	421	408	393	9.03
Static bending strength, MPa	$\sigma_{1\text{-}30}$	84.67	83.65	82.76	82.45	81.79	3.40
	$\sigma_{31\text{-}60}$	89.26	86.86	85.01	84.01	83.01	7.00
	$\Sigma_{61\text{-}90}$	93.96	91.15	88.94	87.68	86.49	7.95
Splitting strength along fibers, MPa	$\tau_{1\text{-}30}$	8.19	7.92	7.69	7.57	7.48	8.67
	$\tau_{31\text{-}60}$	7.92	7.75	7.62	7.53	7.47	5.68
	$\tau_{61\text{-}90}$	7.80	7.65	7.54	7.49	7.45	4.49
Modulus of elasticity in compression, MPa	E_α	11392	11222	11111	11002	10949	3.89
	E_r	739	720	704	693	685	7.31
	E_t	466	460	455	450	447	4.08
Modulus of elasticity in static bending, MPa	$E_{1\text{-}30}$	10602	10331	10125	9975	9898	6.64
	$E_{31\text{-}60}$	11066	10887	10771	10657	10602	4.19
	$E_{61\text{-}90}$	11441	11319	11321	11169	11126	2.75

Table 9. Statistical characteristics of physical and mechanical parameters of fir PCW (10 years)

Parameters		n	$\overline{M}$	M_{min}	M_{max}	±	V, %	P, %	S
Static hardness, MPa	H	48	25.5	21.6	28.4	0.28	7.57	1.0927	1.93
Maximum swelling, %	α_t	48	6.26	5.3	7.0	0.09	9.76	1.4085	0.61
	α_r	48	3.98	3.4	4.4	0.05	8.43	1.2169	0.34
	α_l	48	0.33	0.3	0.4	0.00	8.81	1.2716	0.03
	α_v	48	10.85	9.2	12.1	0.07	4.78	0.6906	0.52
Coefficients of swelling	K_t	48	0.209	0.2	0.2	0.00	8.59	1.2401	0.02
	K_r	48	0.133	0.1	0.1	0.00	9.89	1.4274	0.01
	K_l	48	0.011	0.0	0.0	0.00	7.57	1.0927	0.00
	K_v	48	0.36	0.3	0.4	0.00	4.36	0.6295	0.02
Transverse anisotropy value	α_t / α_r	48	1.57	1.3	1.7	0.01	5.35	0.7727	0.08
Density, kg/m³	ρ_8	48	421	357.4	468.8	5.78	9.51	1.3727	40.04
Static bending strength, MPa	$\sigma_{1\text{-}30}$	48	82.76	70.3	92.2	0.54	4.51	0.6506	3.73
	$\sigma_{31\text{-}60}$	48	85.01	72.2	94.7	0.71	5.81	0.8379	4.94
	$\Sigma_{61\text{-}90}$	48	88.94	75.5	99.0	0.88	6.84	0.9874	6.08
Splitting strength along fibers, MPa	$\tau_{1\text{-}30}$	48	7.69	6.5	8.6	0.03	2.84	0.4105	0.22
	$\tau_{31\text{-}60}$	48	7.62	6.5	8.5	0.04	3.34	0.4821	0.25
	$\tau_{61\text{-}90}$	48	7.54	6.4	8.4	0.05	5.03	0.7264	0.38
Modulus of elasticity in compression, MPa	E_α	48	11111	9433.2	12372.3	58.01	3.62	0.5221	401.94
	E_r	48	704	597.7	783.9	1.76	1.74	0.2505	12.22
	E_t	48	455	386.3	506.7	5.66	8.62	1.2443	39.22
Modulus of elasticity in static bending, MPa	$E_{1\text{-}30}$	48	10125	8596.1	11274.4	63.74	4.36	0.6295	441.59
	$E_{31\text{-}60}$	48	10771	9144.6	11993.7	49.66	3.19	0.4611	344.07
	$E_{61\text{-}90}$	48	11321	9611.5	12606.2	59.35	3.63	0.5242	411.18

Conclusions

1. It is substantiated that PCW is a potential and suitable wood resource for the woodworking industry.
2. The problem of the current inefficiency of using PCW has been highlighted, which is due to the lack of a normative base where the physical and mechanical properties of PCW of the widespread species of wood of various service life would be specified.
3. In order to use PCW in woodworking and to fill the scientific base with the physical and mechanical indicators of fir wood of different ages with an expired product service life, the following characteristics were investigated: static hardness, maximum swelling, coefficients of swelling, the value of transverse anisotropy, density, static bending strength, splitting strength along the fibers, modulus of elasticity in compression, modulus of elasticity in static bending.
4. The characteristics of PCW of the widespread fir species in the range of use from 0 to 20 years were explored, with intermediate control over the properties every 5 years.
5. The dynamics of the physical and mechanical indicators of fir PCW were revealed and it was found that in the course of operation time in various conditions they change, mainly decreasingly: static hardness by 9.2-9.6%; the value of transverse anisotropy by 30-32%; strength: static bending strength by 3.4-7.95%, splitting strength by 4.49-8.67%;

modulus of elasticity: in compression by 3.89-4.08%, in bending by 2.75-6.64%. The main causes of changes in the properties of PCW with age: natural: weathering, partial internal rot, insect damage, other biological effects; mechanical: splitting, scratches, small holes from means of fastening and other defects from use; operational: the influence of power and dynamic loads, the influence of surface finishing agents and other factors on the structural elements of wood products.

6. A summary table was developed for the selection of indicators of the physical and mechanical properties of fir PCW of different ages. When knowing the indicators and dynamics of the physical and mechanical properties of PCW with age, it can be recommended for the manufacturing structural materials: with mechanical damage visible on the surface, and color changes for the manufacture of blockboards, with high-quality surfaces – for the manufacture of furniture panels.
7. Knowledge about the physical and mechanical properties of fir PCW of different ages was further developed; the application of this knowledge made it possible to effectively use this additional resource in woodworking and develop mathematical models for predicting the characteristics of structural materials.
8. The practical significance of the obtained results lies in the fact that the results of studies on the indicators of the physical and mechanical properties of fir PCW of different ages made it possible to understand the dynamics of these indicators, to fill the regulatory database and compare these indicators with the properties of primary wood.

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