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THE INVESTIGATION OF PHYSICAL AND MECHANICAL PROPERTIES OF WOOD PARTICLEBOARDS MADE FROM POST-CONSUMER WOOD

It is found that post-consumer wood (PCW) is as yet non utilized resource of wood waste that is suitable for manufacturing wood particleboards (WPB). It is found that graded chips from PCW (solid wood) of categories I and II are characterized by a standard fraction content (no less than 80 %) and meet the requirements for chips, PS GOST 15815-83. The shreds from clean: PCW when obtained on the standard equipment similar to that which is used for processing primary raw material do not differ essentially by geometrical configuration, size as well as fraction composition from shreds obtained from conventional wood. The high anisotropy factor of the wood particles gives grounds to expect high strength values for WPB made from PCW.

Investigated was the influence of the PCW and binder contents in each of the layers on physical and mechanical properties of three-layer particleboards: bending strength, tensile strength perpendicular to plane, and thickness swelling. Obtained were adequate mathematical models of dependence of WPB physical and mechanical properties on the PCW contents in each layer and the binder.

Production techniques for PCW-containing three-layer particleboards were developed. It was established that optimal production conditions for standard quality panels (DSTU 10632:2009) should correspond to: for panels of PA type (13 MPa) – PCW content in the core and the face layers of the panels may amount to up to 60 % with the average glue consumption of 11.5 %; for panels of PB type (11.5 MPa) – PCW content may amount to 100 % in the core, and 80 to 100 % in the face layers with glue consumption of 7 to 8 % in the core and 10 to 11 % in the face layers. The resulting effect of using PCW in WPB manufacture was estimated for Swisspan Ltd. enterprise, which lies in the fact that, due to PCW utilization, conventional wood expenditures are reduced by 9.4 %.

Keywords: wood, post-consumer wood, wood particleboard, chips, shreds, fractional composition analysis, physical and mechanical properties of panels, bending strength, tensile strength perpendicular to plane, thickness swelling, eco-economic effect.

Topicality of the subject matter. Large-scale cutting down of forests and the resulting environmental impacts, wood resource scarcity – all these force the woodworking industry to seek for alternative sources of raw material [9-27]. The prospective resource that could be used as the raw material base for wood particleboard manufacture, is PCW [1]. This category of wood waste has been making successfully a sort of «career» over the last several decades, especially in West European countries. PCW includes all kinds of wooden material that is available at the end of its use as a wooden product. Such wood mainly comprises demolition wood, packaging material, used furniture [2]. PCW may contain fire retardant material, wood preservatives, paints, varnishes, glues, artificial films, metal, and even glass (windows) [3].

Because of its very different composition, the presence of various kinds of impurity as well as the lack of appropriate machines for its conversion into valuable raw material, the industries of many countries do not always display great interest in this promising source of wood raw material. That is why, PCW, like other industrial wood waste is mainly landfilled. Millions of tons of wood waste have accumulated on the long-standing refuse dumps [4]. The amount of the accumulated waste is too large to be naturally decomposed [5-10].

Thus, the present study is devoted to solving the problem which is important and pressing both for industry and the environment: replenishment of the raw material base.

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The aim of the paper. The present scientific work is aimed at developing resource-saving technology and scientifically based recommendations concerning utilization of PCW to manufacture WPB.

The object of study. Development of resource-saving production methods for the use of PCW to manufacture wood-based panels.

The subject of study. Regular effects of technological parameters on the quality of PCW-containing WPB.

Methods of study. A number of methods were used in the study, namely, experiments, measuring and comparison. The wood particles from conventional wood and PCW were obtained by way of cutting and chipping. The test specimens of panels from PCW were made by way of flat pressing in the hydraulic press. In order to reduce the number of systematic errors during the experiments, the method of randomization was used. During the determination of wood particles from green wood and PCW, the following research methods were applied: physical research methods to determine fractional composition of the particle, the particles moisture content, density, and thickness swelling; mechanical methods to determine the bending strength and tensile strength perpendicular to plane. The experimental data were processed by method of statistical analysis. Also, a comparison was made between the panels made from PCW and the panels made from conventional wood to check the conformity to the standards [28-33].

Scientific novelty of the findings. On the basis of the experimental results obtained, the feasibility of PCW utilization for manufacturing flat-pressed particleboards with adequate physical and mechanical qualities was substantiated.

The optimal ratio of the components of the chips-glue furnish with the addition of PCW was developed, which ensures the production of P-A type of WPB according to DSTU 10632:2009 [11]. Regression dependences were obtained for bending strength, tensile strength perpendicular to plane, thickness swelling versus PCW content in the face layers and the core, various glue consumption as well as pressing parameters (temperature, pressing time, and pressure); these can be used for calculating technological parameters of particleboard manufacture.

The technique for obtaining wood particles from PCW. During the studies, demolition wood was used as raw material (Fig. 1), this wood was not dissimilar in outward appearance to primary wood, although it was about 40 years old [7].

The raw material was chipped into small particles at the enterprise of “Hemmel-Ukraine” company. The chipping was done on the mobile RM-800.4 chipper. The RM-800.4 chipper is fitted with a 30 kWatt electric motor which allows the use of the machine under condition of the enterprise or nearby a source of electric power. This type of chipper is designed for chipping wood waste into chips of 10 sm long, 10 to 25 mm wide, 3 to 5 mm thick. The diameter of the cutter disk (which is fitted with ant jamming system) amounts to 795 mm, the arrangement of disks is favourable for optimal feed of wood, and also it reduces the disk wear. The speed of disk rotation is 1000 rpm, the output of the equipment of this type is about 10 to 15 m^3/hour.

The resulting chips were further converted into shreds (Fig. 2) in the RM 800.7 shredder. The plant is equipped with a dosing bin from which the material is fed through the charging opening into the mill. The grinding is executed due to the high speed of the core rotation – 1480 rpm. The ground material is then sifted through the screen the mesh openings of the which are 10×10 mm, this determining the output fraction size. This type of machine ensures the finest possible grinding of chips to the size of 0 to 10 mm owing to its cutters the number of which is 40 pcs. The productivity of such machine is 8 m^3 per hour. The plant is driven by a 30 kWatt electric motor. The moisture content of the wood particles prior to chipping amounted to 12 %. The wood particles obtained are first subjected to drying and screening, then they are moved further for forming various layers of mat. The drying operation was performed in the drying oven to reach the oven-dry weight at the initial temperature of 200°C. The screening operation was performed on the laboratory-type screen where the wood particles were separated into two fractions: core particles and particles for forming face layers.

Fig. 1. Post-consumer wood

Fig. 2. Chips obtained from PCW

Comparative analysis of chips. Depending on the factor of cutting and the degree of its effect, the process of wood chipping is characterized by the quality of chips obtained and the operating parameters of chipping. The shape of PCW particles should be characterized above all qualitatively (pin-shaped, twisted, cube-shaped, fibrous particles) rather than quantitatively (PCW species, density, bulk density, size distribution curve, etc). There are methods of screen analysis for measuring sample particle size and calculation of arithmetical mean length, width and thickness. However, in actual practice, the methods of qualitative estimate of wood particles are dominant.

The parameters that provide quantitative characteristics (particles size, their ratio, specific surface, "ends area") are not controlled accurately and are not related to each other, the methods of measuring them do not allow for accurate quantitative values that could be used to calculate composite material composition and to develop techniques for manufacturing panels with prescribed qualities with a minimum of glue and energy consumption. Therefore, the critical characteristics of PCW particles are the chips fractional size and composition. In order to compare the geometry and fractional composition of chips, we used primary conventional wood and PCW (Fig. 3, Fig. 4).

In order to measure the moisture content of wood particles, a s 200 hygrometer was used. The principle of the instrument operation is based on measuring dielectric constant and loss tangent of the controlled material in the electromagnetic field created by ring contacts of the instrument transducer. The depth of the field penetration into the interior of the material is 30 to 50 mm, which allows the moisture content of the study material to be measured without impairing its outward appearance.

The selection of measurement mode according to wood species or the type of material is done by means of momentary pressing the button, this is followed by sequential appearance of symbols H1,…H6, E1,…E5 on the liquid crystal indicator. On selection the mode of measurement one should wait until the automatic tuning is completed outdoors and then to continue working. The measurement mode is selected by using the tabulated data in the instrument certificate or on the back cover of the instrument.

Fig. 3. Primary wood chips

Fig. 4. PCW chips

The process of moisture content measurement consists in direct touching the study material with the three-ring contacts (Fig. 5).

Geometrical dimensions of the chips were determined by measuring separate particles thickness, width and length along the wood fiber direction. The number of measurements in the study amounted to no less than 100. The average size of chips was determined from the data obtained by measuring a definite number of particles. The measurements of geometrical dimensions indicates the quality of a separate chip, while the fractional analysis allows for determining the shares of coarse, standard, and fine fractions in the total weight.

The dimensions of chip fractional form: –/10; 10/7; 7/5; 5/3; 3/2; 2/1; 1/0,5; 0,5/0. The sifting of the chip batch was done by means of a 71-GP screen analyzer (Fig. 6).

Fig. 5 Moisture content of PCW chips

Fig. 6. Determination of PCW chip fraction

In the process of the fractionating screen analysis, the weight of each traction was determined by means of analytical balance to an accuracy of 0,01 g. The amount of each fraction is expressed as a percentage to the total weight of the batch. The number of particles for the fractionating analysis was taken so that the whole quantity of the selected particles was used with nothing left over. When selecting a portion of particles from a large quantity, the method of quartering was used since finer fraction in the bulk of particles tends to fall down. The selected portion of particles weighing as much as 50 to 100 g was sifted by means of screen analyzer, fitted with a set of round screen 200 mm in diameter, five of them possessed circular holes of diameter 10, 7, 5, 3, 2, 1 mm, and two ones possessed wire net with meshes measuring 0,5×0,5 and 0,25×0,25 mm.

On a 5-minute sifting, the material obtained was divided into eight fractions (Fig.7): –/10, 10/7, 7/5, 5/3, 3/2, 2/1, 1/0.5, 0.5/0. The results of the study of wood particles geometric dimensions show that fraction content practically does not vary with respect to wood particles from conventional wood (Table 1), although the amount of fine fraction (fraction content 1/0) is two time as much.

Table 1.Comparative analysis of chip fractional composition

Type of wood	Fraction content, %							
	–/10	10/7	7/5	5/3	3/2	2/1	1/0,5	0,5/0
Conventional wood	0,5	2,3	2,6	32,1	28,9	20,6	10,6	2,4
PCW	0,4	1,0	1,8	28,3	25,2	19,3	19,1	4,9

The length, width, and thickness of particle fractions 2/1, 1/0.5, 0.5/0 were determined by way of measuring the particles projection magnified by means of slide projector. The statistical processing of the comparative experiments results was done according to GOST 16483.0-89.

The mean dimensions of chips in a batch involved were determined on the basis of the mean dimensions of an individual chip (length, width, and thickness) in each fraction.


a

b

Fig. 7. Wood particles for: *a) the core b) the face layers*

The impact of structural and technological parameters on panels' strength values is demonstrated through the mediation of dimension less geometrical characteristic of chip formation: degree of contact area. It was foundthat the degree of contact area is dependent on the size of wood particles, namely, the values of bending strength and tensile strength perpendicular to plane as chip fractional composition changes from fraction 5/3 to fraction 10/7. Wood particles from conventional wood and PCW do not have a significant deviation of the fractional content.

One of the main factors which is absent in PCW is bark. The values of physical and mechanical properties of bark are considerably lower than those of sound wood.

The bonding between bark particles as well as between bark particles and wood particles is less strong than that between purely wood particles. Therefore, the addition of bark particles into chips lowers the strength of panels made from conventional wood.

The study of the process of manufacturing particleboard from PCW. ***Selection of the evaluation criterion.*** WPB as a structural material is characterized by a number of factors on the basis of which we can discuss the material quality and its suitability for a specific purpose. In turn, physical and mechanical qualities of particleboard are influenced to a great extent by the very structure of the panel, the formation of which is also influenced by a number of factors: the raw material and the equipment used as well as production conditions. The majority of panel parameters are regulated by relevant standards.

When determining the evaluation criteria for the resulting panels, it is necessary to take into account both technological and economic components of the process. This is dictated by the fact that panels made from PCW must meet the requirements for panels of P-A DSTU 10632:2009 [11] while their production cost should not exceed the production cost of the panels made from trunk wood. An important characteristic of physical and mechanical properties of particleboard is their bending strength which is responsible for panel optimal applications. By means of this parameter, it is possible to determine the optimum manufacturing conditions, PCW chip content and the least binder consumption in order to obtain high-quality panels (strength, roughness and toxicity).

The above said considered, bending strength is taken as the criterion for evaluation of the results of panel manufacture. Besides, there are other parameters which can serve as criteria for the evaluation of panel quality. These are tensile strength perpendicular to plane and thickness swelling.

Investigation planning. Since the process of manufacturing and testing WPB made from PCW was investigated under laboratory conditions, multifactor planning was applied: full-factorial plan. During the experiments, the following factors were taken as variable factors: the contents of the binder and PCW particles both in the core and the face layers. The values for PCW chips content for each layer varied from 20 to 100 % – the rest were standard technological chips; the binder content in each layer was within the average consumption norm ranging from 7 to 16 %.

The levels of factors and factor-change intervals as well as planning matrix in coded values (CV) and actual values (AV) are given in Tables 2-3.

Table. 2. The levels of factors-change interval under investigation

№	Name	Value denotation		Change in interval	Factor level					
		AV	CV		lower		datum level		upper	
					AV	CV	AV	CV	AV	CV
1	PCW content in the core, %	P_c	X_1	40	20	-1	60	0	100	1
2	PCW content in the face layers, %	P_f	X_2	40	20	-1	60	0	100	1
3	binder content, %	K	X_3	4,5	7	-1	11,5	0	16	1

For the purpose of reducing the number of systematic errors, the method of randomization was applied which allowed for establishing random sequence of the experiments conducting. The following factors characteristic of panel manufacture, were noted at the fixed levels: density – 700 kg/m; specific pressure – 2.5 MPa; press temperature – 200 ºC; pressing time – 0.35 min/mm moistures content of the particles for the core – 2 %; moistures content for the face layers – 4 %; the ratio of the layers – 50/50; three-layer panels of 16 mm thick.

Table. 3. Matrix of planning of full-factorial plan – 2^3

№	Values of input factors in the experiment						Serial number				
	AV			CV							
	P_c	P_f	K	x_1	x_2	x_3	1	2	3	4	5
1	20	20	7	-1	-1	-1	20	2	5	13	23
2	100	20	7	1	-1	-1	35	6	16	32	9
3	20	100	7	-1	1	-1	28	19	22	10	11
4	100	100	7	1	1	-1	1	33	24	4	12
5	20	20	16	-1	-1	1	36	25	8	7	26
6	100	20	16	1	-1	1	15	40	34	31	38
7	20	100	16	-1	1	1	14	17	27	18	29
8	100	100	16	1	1	1	37	39	3	21	30

Board manufacturing process. The process of fabricating specimens consists of four steps: preparation of the binder, resin-treatment of the particles, mat formation (Fig. 8) and pressing. A UF-WT-15 urea-formaldehyde resin was the basis for the binder, the resin concentration was reduced by adding water: 64.7 to 62 % for the core and up to 58 % for the face layers. The resulting board is presented in Fig. 9.

Fig. 8. Forming of mat

Fig. 9. Particleboard pressed from PCW

Thus prepared adhesive solution was used for the cores and the face layers. In the process of particleboard manufacture, ammonium chloride (20 % solution) is used in the fallowing amounts: for the core – 1.5 %, for the face layers – 0.5 %, which was mixed with the resin prior to applying it the chips.

The calculation of required proportions of wood particles, resin, curing agent for obtaining specimens of required density as well as the relationship between face layers, the core, and the particleboard thickness, was performed according to the recommendations of the enterprise. The blending of the wood particles, binder and curing agent was done by hand and in a slow manner with the help of electric drill. The chips and the binder were fed in a three-step process by using a compressor to achieve a uniform soak of the wood particles. The process of blending was done separately for each layer according to the prepared quantity of batch.

The forming of mats was also done by hand. The following accessories were used: two metal sheets (pallets), wooden box of 0.5×0.5 m, two metal stops of 0.016 m to control panel thickness. The forming of the panel was done in the wooden box by even distribution of the wood particles on the pallet to form three layers in the 25:50:25 ration. The loss of resined chips made up no more then 7 %. The formed mat was pressed in the single-platen batch press into a panel all required parameters of pressing being observed in doing so. The temperature of the press platen was controlled by thermometer the error of which did not exceed 5 ºC. The panel thickness was controlled by the stops the deviation of which made up ±0,05 mm from the preset thickness.

The press cycle τ_c consisted of: the time τ_{con} needed to charge the press, the time τ_{cl} needed for the platens to close up to the preset thickness, reaching the preset pressure, pressing time τ_p which includes compression time τ_{com} as well as the time τ_o needed to lower the pressure and open the press. The press time τ_{pr} is counted from the moment of reaching a maximum of preset pressure to the moment when the press platens begin to open.

In order to ensure a maximum of strength, to reduce warpage ("spring up") and free formaldehyde release, the panels were conditioned separately from one another. This is accounted for by the fact that the elevated temperatures that may persist in closed stacks of panels up to 5 days (this is especially true for the central part of the stack) cause the destruction of cured glue, which, in turn, results in deterioration of the outward appearance of particleboards, increasing the content of free formaldehyde as well as degradation of their physical and mechanical properties.

Physical and mechanical testing. The determination of the WPB physical and mechanical properties was carried out 5 days after the panels were pressed. The PCW-made panels were cut on the circular saw bench to size specified for specimens testing according to GOST 10633-78; GOST 10634-88; GOST 10635-88; GOST 10636-90 [12-15].

The tests for the bending strength δ_b and the tensile strength perpendicular to plane δ_t were conducted on the WOLPERT machine according to GOST 7855-84 (Fig. 10, a). The motion speed of the load-carrying head – 60 mm/min, the scale division – 1 kg/sm^2; deviation from the actual value made up – 1%.

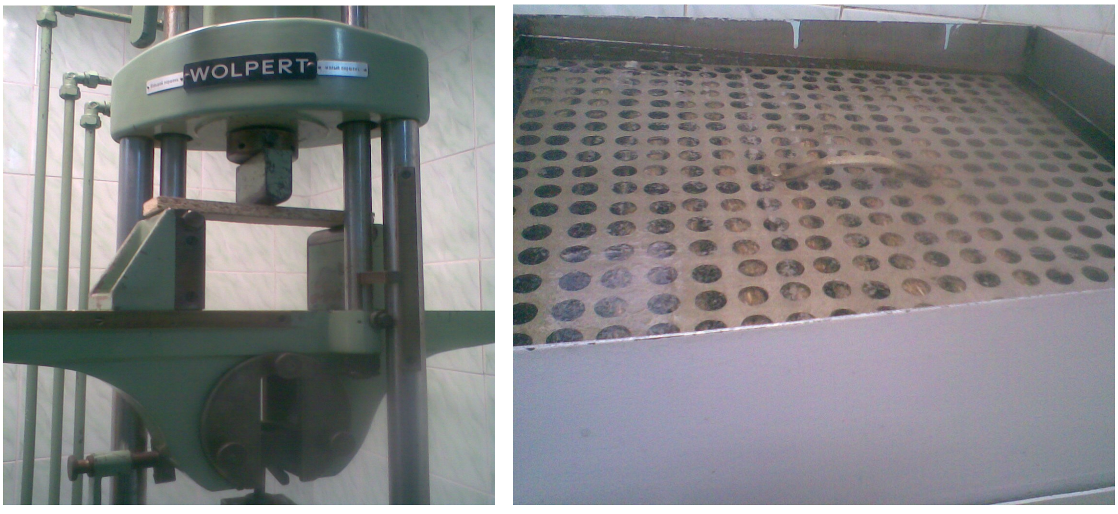


Fig. 10. Determination of test specimens' strength:

a) bending strength *b) thickness swelling*

To conduct the tensile strength perpendicular to plane test, wooden plates were sticked to the test specimens on both sides; thus prepared specimens were subjected to loading for 24 hours. The specimens for determining thickness swelling were placed in water medium of this plant (Fig. 10, b) which houses 40 pieces of specimens, they stood vertically for 24 hours at the constant temperature of 20±1 °C. The swellings can be calculated by the phormula [12]:

$$\Delta h=(h_1-h)/h*100\ \% \quad (1)$$

where: h is the panel's dimensions (length, width, thickness) after conditioning, m; h_1 is the panel's dimensions after water soaking or keeping in humid environment, m.

The results of experimental investigation. The data obtained from physical and mechanical testing of pilot PCW-containing particleboard for bending strength, tensile strength perpendicular to plane, and thickness swelling are shown in Tables 4-6.

Table 4. The results of testing PCW-containing WPB for beading strength

No	Factor value in the experiment						Bending strength measurements, MPa				
	actual values			coaded values							
	P_c	P_f	K	x_1	x_2	x_3	y_{1j}	y_{2j}	y_{3j}	y_{4j}	y_{5j}
1	20	20	7	-1	-1	-1	13,20	13,00	12,90	13,10	12,80
2	100	20	7	1	-1	-1	12,70	13,20	12,80	13,20	12,80
3	20	100	7	-1	1	-1	12,31	12,50	12,30	12,24	12,10
4	100	100	7	1	1	-1	11,80	11,20	12,75	12,00	12,24
5	20	20	16	-1	-1	1	19,50	19,80	19,10	19,90	19,20
6	100	20	16	1	-1	1	19,23	19,32	19,28	19,21	19,11
7	20	100	16	-1	1	1	18,13	18,22	18,40	18,20	18,30
8	100	100	16	1	1	1	18,80	17,50	17,40	18,10	18,20

Table 5. The results of testing PCW-containing WPB for beading strength perpendicular to plane

No	Factor value in the experiment						Tensile strength perpehdicular to plane measurement, MPa				
	actual values			coaded values							
	P_c	P_f	K	x_1	x_2	x_3	y_{1j}	y_{2j}	y_{3j}	y_{4j}	y_{5j}
1	20	20	7	-1	-1	-1	0,489	0,51	0,502	0,505	0,495
2	100	20	7	1	-1	-1	0,459	0,465	0,457	0,395	0,457
3	20	100	7	-1	1	-1	0,421	0,431	0,428	0,442	0,436
4	100	100	7	1	1	-1	0,326	0,345	0,344	0,341	0,346
5	20	20	16	-1	-1	1	0,658	0,658	0,647	0,645	0,642
6	100	20	16	1	-1	1	0,611	0,595	0,601	0,611	0,589
7	20	100	16	-1	1	1	0,605	0,623	0,621	0,643	0,637
8	100	100	16	1	1	1	0,585	0,592	0,567	0,549	0,558

Table 6. The results of testing PCW-containing WPB for thickness swelling

No	Factor value in the experiment						Thickness swelling measurements, %				
	actual values			actual values							
	P_c	P_f	K	x_1	x_2	x_3	y_{1j}	y_{2j}	y_{3j}	y_{4j}	y_{5j}
1	20	20	7	-1	-1	-1	17,29	17,13	16,97	17,51	17,34
2	100	20	7	1	-1	-1	17,12	16,94	16,89	16,87	17,20
3	20	100	7	-1	1	-1	16,24	17,69	16,97	16,47	16,87
4	100	100	7	1	1	-1	16,81	16,95	16,93	16,56	16,84
5	20	20	16	-1	-1	1	14,89	14,47	14,28	14,75	14,33
6	100	20	16	1	-1	1	14,29	14,21	14,58	14,17	14,55
7	20	100	16	-1	1	1	14,08	14,08	14,00	14,15	14,21
8	100	100	16	1	1	1	13,94	13,88	13,96	13,79	13,95

On calculating mean values and sample variances, the check on variance homogeneity in the experiments by means of Kohren G-criterion indicated that all the variances were homogeneous. By using similar procedure, the variances of reproducibility of measurements of physical and mechanical properties were calculated: for bending strength: S_{re}^2 = 0.112; for tensile strength perpendicular to plane: S_{re}^2 = 0.0003; for swelling: S_{re}^2 = 0.0646. The root-mean-square deviation for calculated coefficients of regression equations made up: for bend strength: $S\{b_i\}$ = 0.05; for tensile strength perpendicular to plane: $S\{b_i\}$ = 0.0025; for thickness swelling: $S\{b_i\}$ = 0.0402.

On checking regression equations coefficients for meaningfulness and establishing their confidence intervals, the calculations showed that the regression equations coefficients are meaningful except for eight ones (Tables 7-9), but we do not ignore them in consideration of system approach.

Table 7. Checking regression equation coefficients for meaningfulness, their confidence intervals for bending strength

Coefficient	Coefficient value	$t(q,f_y)S\{b_i\}$	Conclusion	Confidence interval boundaries	
				$b_i-t_{tab}*S\{b_i\}$	$b_i+t_{tab}*S\{b_i\}$
b_o	15,651	0,11	Meaningful	15,54	15,76
b_1	-0,119	0,11	Meaningful	-0,22	0,01
b_2	-0,517	0,11	Meaningful	-0,62	-0,41
b_3	3,094	0,11	Meaningful	2,99	3,20
b_{12}	-0,026	0,11	No meaningful	-0,13	0,08
b_{13}	-0,021	0,11	No meaningful	-0,13	0,09
b_{23}	-0,104	0,11	No meaningful	-0,21	0,00

Table 8. Checking regression equation coefficients for meaningfulness, their confidence intervals for tensile strength perpendicular to plane

Coefficient	Coefficient value	$t(q,f_y)S\{b_i\}$	Conclusion	Confidence interval boundaries	
				$b_i-t_{tab}*S\{b_i\}$	$b_i+t_{tab}*S\{b_i\}$
b_o	0,521	0,01	Meaningful	0,52	0,53
b_1	-0,031	0,01	Meaningful	-0,04	-0,03
b_2	-0,029	0,01	Meaningful	-0,03	-0,02
b_3	0,091	0,01	Meaningful	0,09	0,10
b_{12}	-0,006	0,01	No meaningful	-0,01	0,01
b_{13}	0,005	0,01	No meaningful	0,00	0,01
b_{23}	0,015	0,01	Meaningful	0,01	0,02

Table 9. Checking regression equation coefficients for meaningfulness, their confidence intervals for thickness swelling

Coefficient	Coefficient value	$t(q,f_y)S\{b_i\}$	Conclusion	Confidence interval boundaries	
				$b_i-t_{tab}*S\{b_i\}$	$b_i+t_{tab}*S\{b_i\}$
b_o	15,604	0,08	Meaningful	15,52	15,69
b_1	-0,082	0,08	Meaningful	-0,16	0,01
b_2	-0,185	0,08	Meaningful	-0,27	-0,10
b_3	-1,376	0,08	Meaningful	-1,46	-1,29
b_{12}	0,025	0,08	No meaningful	-0,06	0,11
b_{13}	-0,014	0,08	No meaningful	-0,10	0,07
b_{23}	-0,039	0,08	No meaningful	-0,12	0,04

The regression equation coefficients obtained as a result of the full-factorial plan realization possess a clean physical meaning. The coefficient b_o is equal to the output value and of all factors are fixed at the basic level. The sigh of the coefficient b_i points to the nature of corresponding factor influence: if $b_i>0$, the output value tends to increase with an increase of the factor x_i value, and vice versa. The absolute value of the regression coefficient in the model points to the extent to which the response function is affected by the corresponding factor. The higher absolute value of the coefficient, the stronger influence on the output parameter change has the factor to which the given coefficient corresponds. Thus, the extent of the factors effect on the output values can be compared by means of linear regression model and so revealing the most important factors.

In order to evaluate the ability of the obtained models to describe output values with the same degree of accuracy as the experimental results, the mathematical models were checked for their adequacy by Fisher F-criterion by means of which the variances of adequacy $\mathbf{S_{ad}^2}$ and reproducibility $\mathbf{S_{re}^2}$ are compared.

The calculated adequacy variances for physical and mechanical properties of PCW-containing particleboards made up: for bend strength $\mathbf{S_{ad}^2} = 0.040$; for tensile strength perpendicular to plane $\mathbf{S_{ad}^2} = 0.00059$; for thickness swelling $\mathbf{S_{ad}^2} = 0.0306$.

The calculated values for Fisher criterion for physical and mechanical properties of PCW-containing particleboards made up: for bending strength $\mathbf{F_{cal}} = 2.821$; for tensile strength perpendicular to plane $\mathbf{F_{cal}} = 0.437$; for thickness swelling $\mathbf{F_{cal}} = 0.512$.

The tabulated value for Fisher criterion is equal to 250. By comparing the calculated values for Fisher criteria with the tabulated ones, we can see that the inequality $\mathbf{F_{cal}} < \mathbf{F_{tab}}$ is accomplished for physical and mechanical properties of PCW-containing particleboards. That is, the mathematical models obtained are considered adequate and can be used to describe objects. Thus, the calculations done made it possible to obtain the following regression equations of the full-factorial plan with actual factor values for physical and mechanical properties.

$$\boldsymbol{\sigma_b} = 8{,}145 - 0{,}00043 \cdot P_c - 0{,}0053 \cdot P_f + 0{,}729 \cdot K + 0{,}000016 \cdot P_c \cdot P_f + 0{,}00011 \cdot P_c \cdot K - 0{,}00057 \cdot P_f \cdot K;$$

$$\boldsymbol{\sigma_t} = 0{,}442 - 0{,}00088 \cdot P_c - 0{,}0015 \cdot P_f + 0{,}0136 \cdot K + 0{,}0000035 \cdot P_c \cdot P_f + 0{,}000028 \cdot P_c \cdot K - 0{,}000083 \cdot P_f \cdot K;$$

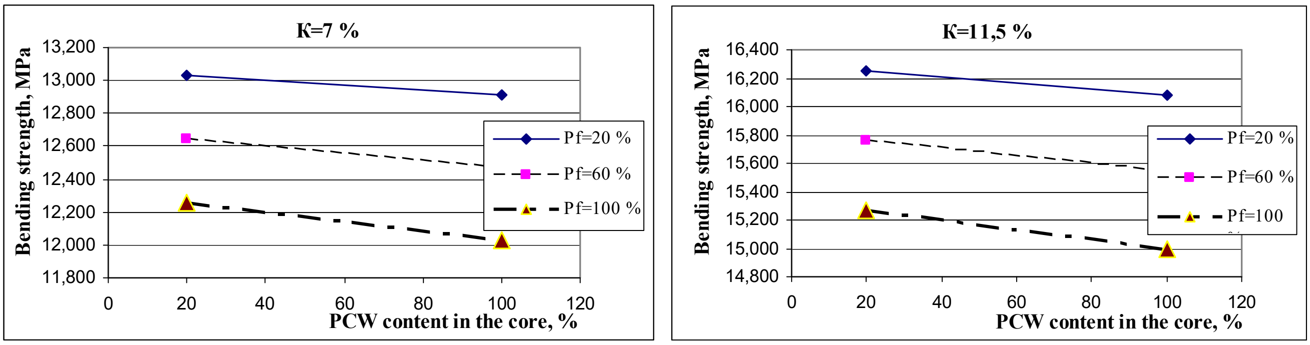
$$\boldsymbol{\Delta h} = 19{,}37 - 0{,}0021 \cdot P_c - 0{,}0031 \cdot P_f + 0{,}288 \cdot K + 0{,}000016 \cdot P_c \cdot P_f + 0{,}000076 \cdot P_c \cdot K - 0{,}00022 \cdot P_f \cdot K;$$

The data of regression equations describe the physical and mechanical properties of PCW-containing particleboards and allow output values to be calculated for any point of the experiment zone provided that $\mathbf{x_i = [-1;+1]}$, where $\mathbf{i = 1, k}$.

Since the influence of factors and their interaction on the response function is best analyzed graphically, three groups of diagrams were constructed by regression equations: the relationship between output value (bending strength, tensile strength, and thickness swelling) and PCW content both in the face layers and core at the constant values for the binder at the minimum, mean, and maximum levels (Fig. 11-13).

Graphical representation of the relationships obtained allows for revealing character of variable factors influence on the properties of the resulting particleboards, since the full-factorial plan was realized here, all the dependences have linear character. As is seen from the diagrams, the PCW content in the particleboards behaves equally at different binder content levels that is the bending strength is decreasing within from 19.469 to 12.030 MPa range, the tensile strength is decreasing within the range of 0.646 to 0.344 MPa, while the thickness swelling is also decreasing from 17.22 to 13.93 %. The diagrams also show that the lines do not run parallel to one another, and the angle of their slope varies as certain variable factors change. This points to the fact that the influence of factors interaction is just as significant as the influence of the individual factors.

Our study has demonstrated that for a given 700 kg/m^3 particleboard density and an average glue consumption of 11.5 %, an increase in PCW chips content in the face layers from 20 to 100 % results in decreased bending strength by 6 % while the same increase in PCW content in the core makes up only 1 %. The use of a 100 % PCW particles content and glue consumption of 11.5 % both in the core and the face layers results in the bending strength of 15 MPa, which is 8 % smaller than for the case of a 20 % PCW content. The conditions being the same, it was found that the tensile strength is essentially influenced by the increased content of PCW particles in the core an decrease in the tensile strength amounted to 9 %. The physical and mechanical properties of the particleboard are most influenced by the glue content. With increasing the glue content, the strength is also increasing (by 30 %) while the thickness swelling is decreasing (by 15 %). The reason for this lies in the fact that there is a greater amount of adhesive spread per unit surface area of the wood particles, and this glue film prevents the water from penetration into the interior of wood particles. Also, due to the absence of bark from PCW particles, there is an increase in the strength by 2 to 5 % in the PCW-containing particleboard compared to panels made from conventional wood.



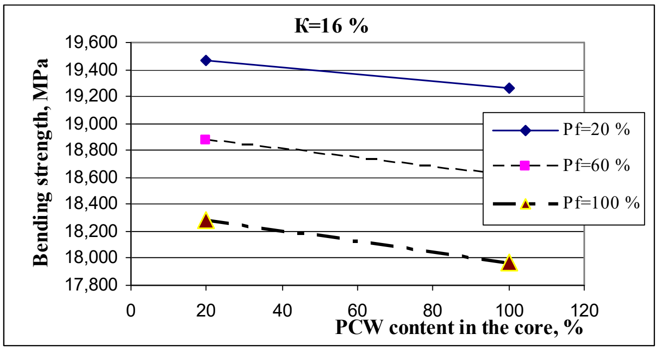
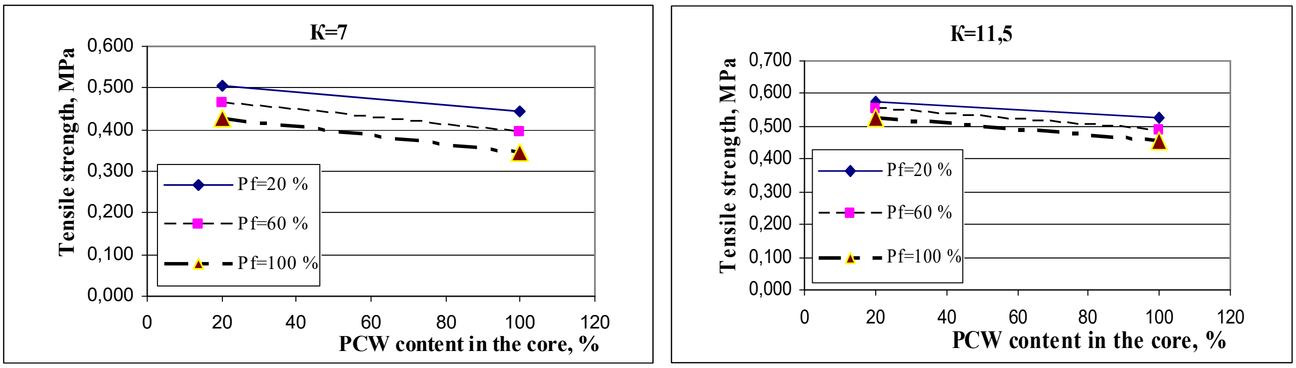


***Fig. 11. Relationship between panel's bending strength and the content of PCW both in the core and face layers as well as the binder content:** a) К=7 %; b) К=11,5 %; c) К=16 %*



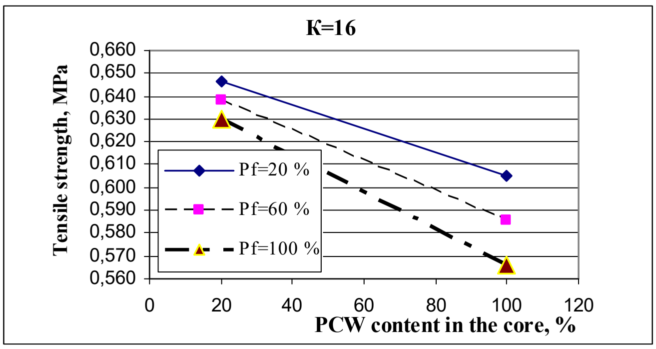
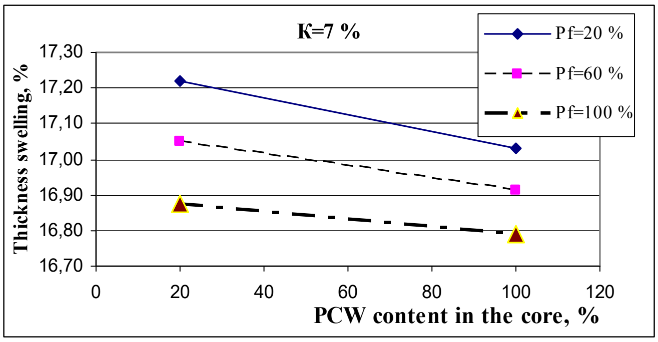
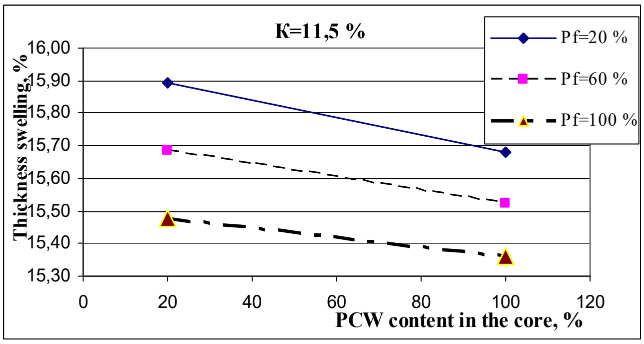


***Fig. 12. Relationship between panel's tensile strength and PCW content both in the core and face layers as well as the binder content:** a) К=7 %; b) К=11,5 %; c) К=16 %*

Thus, WPB that has a 60 % PCW particles content and the glue consumption of 11.5 % produces composite materials that meet the requirements for the P-A type of particleboards according to DSTU 10632:2009 «Wood particleboards. Specifications» [11].





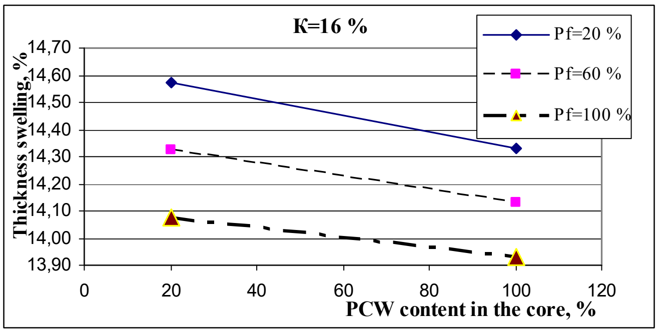


Fig. 13. Relationship between panel's strength at swelling and PCW content both in the core and the face layers as well as the binder content:
a) K=7 %; b) K=11,5 %; c) K=16 %

Conclusions and recommendations:

1. It has been found that PCW of categories I and II (30 to 50 % of the total volume) is an important wood resource and can essentially expand the raw material base for WPB manufacture.
2. Processing procedures for WPB manufacturing have been developed with the use of PCW as raw material. By using Full-factorial, Plan-2^3, a multyfactor experiment was conducted and the planning matrix has been elaborated. It has been found that graded PCW chips (solid wood) of categories I and II are characterized by a standard fraction (no less than 80 %) and meet the requirements for chips PS GOST 15815-83 [16]. The chips prepared from clean PCW, provided that they are obtained on the standard equipment, do not differ essentially by geometry, shape, and fraction composition from those obtained from conventional wood. Investigations have been carried out to assess the influence of PCW and binder contents in each of the layers on physical and mechanical properties of tree-layer particleboard: bending strength and tensile strength perpendicular to plane, and thickness swelling.
3. Adequate mathematical models were obtained for physical-and-mechanical parameters of WPB versus the PCW and binder contents in each later. It has been revealed that for a given 700 kg/m^3 density, the boards made from PCW, depending on the PCW category (quality) and glue consumption, hat a 8 to 10 % decrease in the bending strength and 12 to 32 % decrease in tensile strength compared to boards made from conventional wood, they also meet the requirements for P-A type of particleboards, DSTU 10632:2009 «Wood particleboards. Specification». It has been revealed that thickness swelling for PCW-made particleboards with an average glue consumption of 11.5 % is 3 to 5 % less compared to boards made from conventional wood, also, the glue consumption increase from 7 to 16 % results in the thickness swelling reduction by 18 % under the same manufacturing process conditions. This is accounted for by the fact that PCW particles lose bound moisture after long-lasting usage (20 to 40 years) that is, they become more porous and this, in turn, is responsible for greater amount of these particles per unit volume, thus promoting their greater compactness, which prevents the penetration of moisture. It has been found that the optimum conditions for manufacturing boards of standard quality (DSTU 10632:2009) are as follows: for P-A type (13 MPa) – PCW particles content in the core and the face layers may amount to 60 % with an average glue consumption of 11.5 %; for P-B type of boards (11.5 MPa) – PCW particles content in the core amounts to 100 % and 80 to 100 % in the face layers with glue consumption in the core being 7 to 8 % and 10 to 11 % in the face layers.

4. Estimated was the effect of introducing the results obtained in practice at the Swisspan Ltd. Enterprise, which lies in the fact that the use of PCW in the particleboard manufacture leads' to the reduction of costs for conventional wood by 9.4 % [10].

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Дослідження фізико-механічних властивостей деревинно-стружкових плит із вживаної деревини

Встановлено, що вживана деревина (ВЖД) є незадіяним ресурсом деревних відходів, придатним для виробництва деревинно-стружкових плит (ДСП). Встановлено, що відсортована тріска з ВЖД (масивної деревини) першої та другої категорії характеризується вмістом кондиційної фракції і відповідає вимогам до тріски ПС згідно ГОСТ 15815-83. Стружка із чистої ВЖД, якщо вона одержана на аналогічному обладнанні, яке використовують для перероблення первинної сировини, за геометричними розмірами, формою та фракційним складом не суттєво відрізняється від стружки з традиційної деревини. Досліджено вплив вмісту ВЖД у кожному із шарів та в'яжучого на фізико-механічні властивості тришарових ДСП – міцність при статичному згині, розтягу перпендикулярно до площини плити та набрякання за товщиною.

Графічна інтерпретація одержаних залежностей дозволила обґрунтувати характер впливу змінних факторів на властивості одержаних плит. Оскільки був реалізований повнофакторний план, то всі залежності носять лінійний характер. З графіків добре видно, що вміст ВЖД в діапазоні 20-100 % в ДСП веде себе однаково при різному вмісті в'яжучого. Зокрема, при витраті клею 11,5 % міцність при статичному згині спадає з 16,25 до 15,0 МПа., при розтягу перпендикулярно до площини плити – від 0,575 до 0,455 МПа, а набрякання за товщиною – з 15,90 до 15,36 %. На графічних залежностях також чітко видно, що лінії між собою не є паралельними і кут їх нахилу зі зміною певних змінних факторів різний. Це свідчить про те, що вплив взаємодій факторів є також значним у порівнянні з впливом самих факторів.

Дослідженнями встановлено, що при щільності плити 700 м^3/кг та середній витраті клею 11,5 %, збільшення вмісту стружки із ВЖД у зовнішніх шарах від 20 до 100 % зменшує міцність при статичному згині на 6 %, а таке ж збільшення у внутрішньому шарі приводить до зменшення тільки на 1 %. При 100 % виготовленні плит із ВЖД та середній витраті клею для двох шарів 11,5 % міцність при статичному згині становила 15 МПа, що на 8 % менше, ніж при наповненні деревостружкового килиму на 20 % стружкою із ВЖД. Аналогічно при тих же умовах виявлено, що на міцність при розтягу перпендикулярно до площини плити суттєво вливає збільшення вмісту стружки ВЖД (з 20 до 100 %) у внутрішньому шарі, ніж у зовнішніх. Величина міцності зменшується на 9 %, але відповідає вимогам до плит марки П-А за ДСТУ 10632:2009.

Найбільший вплив на фізико-механічні показники плит має вміст клею. При збільшенні вмісту клею міцніть збільшується, а набрякання за товщиною зменшується. Це зумовлено більшим покриванням деревних частинок плівкою клею, яка перешкоджає проникнення води у середину деревних частинок, а також відсутністю кори в складі ВЖД, яка негативно впливає на процеси склеювання, тобто на фізико-механічні властивості плит ДСП. Крім того, експериментально доведено, що контрольні експериментальні зразки із 100 % використанням традиційної сировини при однаковій витраті клею, мали менші фізико-механічні властивості, ніж плити із 20 % наповненням із ВЖД: межа міцності останніх при статичному згині була більшою на 15 %, при розтягу перпендикулярно до площини плити також більшою на 22 %, а набрякання за товщиною було меншим на 17 %. По-перше, зростання показників у діапазоні вмісту стружки з ВЖД від 0 % до 20 % зумовлене збільшеним вмістом (у два рази) дрібної фракції (1/0) у стружці з ВЖД (табл. 1); по-друге, дрібні частинки заповнюють пустоти і тим самим збільшують площу склеювання, що впливає на показники міцності; по-третє, при добавлянні її до зовнішніх шарів – покращується структура поверхні (шорсткість) одержаних плит, а при добавлянні до внутрішнього шару – неплоска стружка (скручена, кубикоподібна) частково розташовується не в площині плити, а під кутом, що зумовлює більший опір розтягу перпендикулярно площині плити, оскільки на це вливають не тільки клеєві шви, але й волокна деревини.

Таким чином, експериментально встановлено, що при вмісті 60 % ВЖД та середній витраті клею 11,5 % у ДСП, одержані композиційні матеріали відповідають вимогам до плит марки П-А згідно ДСТУ 10632:2009 «Плити деревинно-стружкові. Технічні умови».

Висновки та рекомендації:

1. Встановлено, що ВЖД першої та другої категорій (30-50 % від усього об'єму збирання) є значним ресурсом деревини та суттєвим додатком до основної сировини у виробництві ДСП.
2. Розроблено технологію виготовлення ДСП з використанням в якості сировини ВЖД. За використання ПФП-2^3 проведено багатофакторний експеримент та реалізовано матрицю планувань згідно методики досліджень. Встановлено, що відсортована тріска з ВЖД (масивної деревини) першої та другої категорії характеризується вмістом кондиційної фракції (не менше 80 %) і відповідає вимогам до тріски ПС за ГОСТ 15815-83. Стружка із чистої ВЖД, якщо вона одержана на аналогічному обладнанні, яке використовують для перероблення первинної сировини, за геометричними розмірами, формою та фракційним складом не суттєво відрізняється від стружки з традиційної деревини. Збільшений вміст дрібної фракції (1/0) у стружці з ВЖД у діапазоні вмісту стружки з ВЖД від 0 % до 20 % у плиті зумовлює зростання показників фізико-механічних показників ДСП. Коефіцієнт анізотропії стружок дає можливість передбачати показники міцності плит із ВЖД. 6. Одержано адекватні математичні моделі залежності фізико-механічних показників ДСП від вмісту ВЖД і в'яжучого в кожному із шарів. Встановлено, що при щільності 700 кг/м^3 плити із ВЖД (100 %) мали, в залежності від вмісту ВЖД (20-100 %) та витрати клею, на 8-10 % меншу міцність при статичному згині та на 12-32 % меншу – при розтягу перпендикулярно до площини плити, ніж із вмістом ВЖД 20 %, і, при цьому, відповідали вимогам до плит марки П-А ДСТУ 10632:2009 «Плити деревинно-стружкові. Технічні умови».

7. З'ясовано, що набрякання за товщиною для ДСП із ВЖД (100 %) при середній витраті клею 11,5 % є на 3-5 % меншим, ніж у плит із 20 % вмістом ВЖД, крім того при зміні кількості клею від 7 % до 16 % для тих же умов виготовлення набрякання за товщиною зменшується на 18 %. Причина – деревні частинки із ВЖД після тривалого використання (20-40 років) втрачають зв'язану вологу, тобто є більш пористими, а ще зумовлює їх більшу кількість в одиниці об'єму, що сприяє підвищеному ущільненню їх між собою, тобто зменшує проникнення вологи.

8. Встановлено, що раціональним умовами виготовлення плит стандартної якості (ДСТУ 10632:2009) відповідають: для плит марки П-А (13 МПа) – вміст ВЖД у плиті у внутрішньому та зовнішніх шарах може становити до 60 % при середній витраті клею 11,5 %; для плит марки П-Б (11,5 МПа) – вміст ВЖД у внутрішньому до 100 % та зовнішніх шарах може становити 80-100 % при витраті клею у внутрішньому шарі – 7-8 % та зовнішніх шарах – 10-11 %.

9. Розраховано ефективність від впровадження отриманих результатів виготовлення ДСП з використанням ВЖД на підприємстві ТОВ «Свиспан Лімітед», які полягають в тому, що завдяки залученню ВЖД, зменшаться витрати на традиційну деревину на 9,4 %.

Ключові слова: деревина, вживана деревина, деревинно-стружкова плита, тріска, стружка, аналіз фракційного складу, фізико-механічні властивості плит, міцність при статичному згині, міцність при розтягу перпендикулярно площині, набрякання, еколого-економічна ефективність.