Analysis of Physical-Mechanical Characteristics and Advantages of Bakelite Plywood as Constructional Material

***[1] Dmitry D. Koroteev, [2]Farid A. Boytemirov**

[1] Department of Architecture & Civil Engineering, Peoples Friendship University of Russia (RUDN University), Moscow, Russia

[2] Department of Metal & Wooden Structures, Moscow State University of Civil Engineering, Moscow, Russia

* Corresponding Author: Dmitry D. Koroteev

Email: d241184@gmail.com

https://doi.org/10.26782/jmcms.2019.03.00014

Abstract

Waterproof plywood as product of the wood reprocessing has the number of advantages for civil engineering, such as: ability to form curved surface; transportability and possibility of quick erection; relatively large size and similar physical-mechanical properties in lengthwise and crosswise direction; resistance against chemical and biological influence. Bakelite plywood is one of the prospective types of waterproof plywood.

The effective introduction of bakelite plywood into civil engineering slows down because of insufficient knowledge of influence of the range of factors on strength and deformability of the bakelite plywood structures. Taking into account the above, the research work is devoted to study physical-mechanical properties of bakelite plywood as orthotropic material. The aim of the research is to obtain the results, which can be used for design of the bakelite plywood structures.

Samples with size 30x30x120 mm, made by bonding the required number of 9-layers plywood sheets with the use of phenol-formaldehyde glue, were used to determine mechanical-physical characteristics of bakelite plywood. The sheets with thickness of 10 mm were used in the research work. Every sample was tested by sixfold loading and unloading with measurement of deformations in the process of loading.

The research results of physical-mechanical properties of bakelite plywood as orthotropic material are shown in the article. They are necessary for practical calculations of tensions in the adhesive joints by methods of elastic theory of anisotropic materials. The possibility of using the obtained research results for practical calculations is shown on the example of the overlapping adhesive joint.

Keywords : Bakelite Plywood, Orthotropic Material, Physical-Mechanical Characteristics, Adhesive Joint, Modulus Of Elasticity

I. Introduction

One of the effective products of the wood reprocessing nowadays is plywood, especially waterproof plywood. The use of waterproof glues provides possibility of manufacturing and wide application of waterproof plywood (Luo et al., 2016; Tang et al., 2011; Lei et al., 2014).

The research results show that 1 m^3 of plywood replaces more than 4 m^3 timbers and saves about 3.5 m^3 softwood, which can be used in other fields of industry (Bekhta et al., 2009).

Plywood sheets have relatively large size and similar physical-mechanical properties in lengthwise and crosswise direction (Frolovs et al., 2017; Yoshihara, 2009). Values of linear deformations during desiccation of plywood sheet are less than 0.1% thanks to multilayer cross structure (Li et al., 2014; Windt et al., 2018). Influence of natural defects of wood on mechanical strength of plywood is low (Khasanshin et al., 2016). World building practice shows that laminated wood and plywood can be used for most modern structures, building from steel and reinforced concrete. In this case, the structures can be light in weight in 4-5 times. The achievement, reflecting potential possibilities of modern plywood structures, is structures of stadiums and shopping malls in different countries with the span length more than 100 m.

Valuable property of plywood structures is their transportability and possibility of quick erection, which allows constructing makeshift buildings and timely transporting them to new places. The ability of plywood to form curved surface allows using it for grain storages, silos, fuel tanks and so on. Structures from waterproof plywood in many cases can effectively replace steel structures, reducing weight of constructions and providing the required durability (Toksoy et al., 2006). Three-layer plates and panels with cover from waterproof plywood have particular interest thanks to their strength and water resistance (Aicher et al., 2016; Aydin, 2004). They are used in different slabs and coating plates, which is designed for load of 350 kg/m^2 and span length of 10-12 m (Candan and Akbulut, 2014; Demirkir et al., 2013).

Bakelite plywood is produced from birch veneer, impregnated and bonded by phenol-formaldehyde glue. External layers of bakelite plywood are bonded with internal layers and impregnated by waterproof synthetic resin (Kim et al., 2015; Muttil et al., 2014). It differs from usual plywood by high strength, water resistance and durability in process of maintenance. Bakelite plywood chars when temperature increases up to 350 °C and does not provide the burning process. It effectively resists chemical and biological influence; it means that bakelite plywood is not affected by mild acids and alkalis, as well as mold and bugs (Koroteev et al., 2017).

The above-mentioned advantages of bakelite plywood open a wide possibility of using it for civil engineering, especially for structures of residential and industrial buildings, reusable formworks and special constructions. It is especially important for rural construction, places of oil and gas production, seismic areas (Zhou et al., 2016). It is necessary to reduce materials consumption and increase physical-mechanical characteristics of plywood structures for their successful using. In this case, the use of bakelite plywood as construction material is one of the perspective ways to design modern structures of buildings with various functions.

However, the effective introduction of bakelite plywood into civil engineering slows down because of insufficient knowledge of influence of the range of factors on strength and deformability of the bakelite plywood structures. Taking into account the above, the research work is devoted to study physical-mechanical properties of bakelite plywood as orthotropic material. The aim of the research is to obtain the results, which can be used for design of the bakelite plywood structures.

II. Research methodology

Bakelite plywood is a waterproof material, consisting of odd number of the birch veneer layers. They are impregnated by phenol-formaldehyde resin and bonded under relative perpendicular position of fibers in adjoining layers.

It is common knowledge that the strength of plywood and its plastic properties rise with the increase of its volume weight, which is more than wood and depends on the bonding mode, number and thickness of veneer.

The tensile and bending strength of bakelite plywood is more than 100 MPa with γ=1.1 tone/m^3. Bakelite plywood with thickness of 10 mm was used in the research work.

Bonding process is one of the effective ways to join modern constructional materials. Waterproof glues are more important for the plywood structures development than welding for steel structures (Lokaj and Vavrusova, 2017; Moubarik et al., 2009). The glues, used for bonding of tense elements of plywood structures, should provide strength of the adhesive joint not less than the shear strength of wood lengthwise the fibers and stretch strength crosswise the fibers (Fang et al., 2014; Tan et al., 2011). The adhesive joints in stretched and bended elements are usually made using one or two plates and overlapping.

Plywood, as laminated wood material with cross position of the wood fibers in adjoining veneers, is orthogonal-anisotropic (orthotropic) material. Plywood, as orthotropic material, has three relative perpendicular positions of elasticity: lengthwise X(1) and crosswise Y(2) of the veneer in the sheet surface, perpendicular to the sheet surface Z(3) (fig. 1).

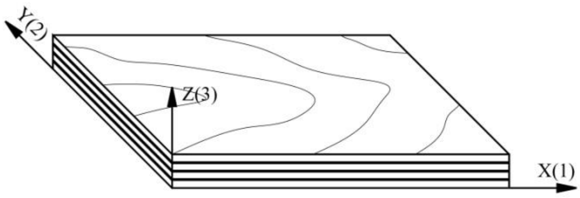

Fig. 1. Positions of elasticity of plywood sheet

It is necessary to know elastic properties of plywood in the surface, which is perpendicular to the sheet surface and coincides with the main positions of resilience by axes 1 and 3 if we need to determine tensions in the adhesive joint of anisotropic material. Plywood is not homogeneous in this surface, but we assume homogeneity of the material with the average values of elastic properties by sheet thickness for practical rough calculations. These properties are modulus of elasticity along axes 1 and 3 (E_1 and E_3); shear modulus in the surface of these axes (G_{13}) and coefficient of cross deformation under load along axis 1 (υ_{13}).

Samples with size 30x30x120 mm, made by bonding the required number of 9-layers plywood sheets with the use of phenol-formaldehyde glue, were used to determine mechanical-physical characteristics of bakelite plywood (fig. 2). Ratio between height and width of the samples, equal to 4, was accepted due to risk of influence of tightness of deformations in bearing parts of the samples on the experiment results.

Modulus of elasticity (E_1) was determined by testing the samples (fig. 2, a) with measurement of deformations along the axis of the sample on two parallel edges. Coefficients of cross deformation (υ_{13} and υ_{12}) were determined by simultaneous measurement of cross deformation on the edge, coinciding with axes 1 and 3, and the perpendicular edge. The coefficients of cross deformation were determined as ratio between relevant crosswise and lengthwise deformations.

Shear modulus (G_{13}) was determined by formula (1).

$$G_{13} = \frac{E_{45}}{2(1+\upsilon_{45})} \tag{1}$$

where E_{45} – modulus of elasticity in the surface of axes 1 and 3 under angle 45° to these axes, which is determined on the samples (fig. 2, c);

υ_{45} - coefficient of cross deformation, determined on the same samples.

Modulus of elasticity (E_3) was determined by measurement of lengthwise deformation of the sample with crosswise position of veneer (fig. 2, b).

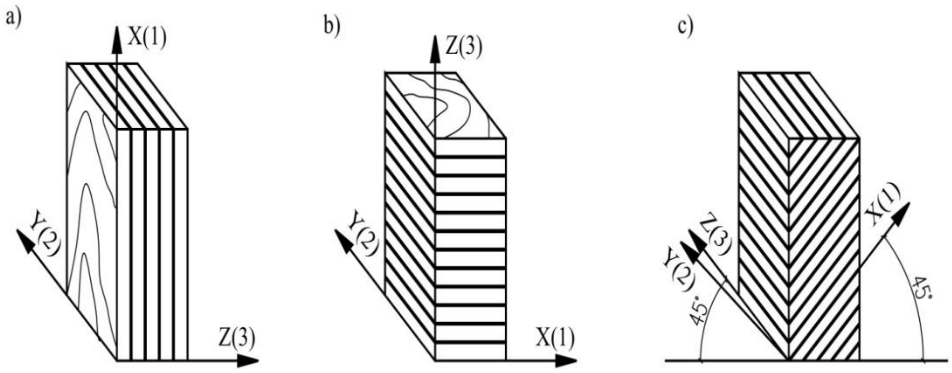

Fig. 2. Samples from 9-layers bakelite plywood
a) sample (type a); b) sample (type b); c) sample (type c)

Compulsory necessity to bond the samples from solid sheets of plywood can cause some variations of deformations of the sample and particular plywood sheet. For example, two additional bonding seams (fig. 2, a) influence on the results of determination of lengthwise deformations, one additional veneer on the base of measurement influences on the results of determination of crosswise deformations.

However, approximate assessment of influence of the bonding number on the samples deformation, made in view of elastic properties of glue and veneers depending on the wood fibers orientation, shows that this influence is low. The assessment shows that relative deformation along the axis of the samples (fig. 2, a) is 2% less than similar deformation of the particular plywood sheet under the same tension. The relative deformation difference of the samples (fig. 2, b) and the particular plywood sheet in crosswise orientation of the veneers is less than 1%.
Strain gauges were used to determine deformations on the sample parallel edges. The bottom of the strain gauge was placed on linings with size 3x5 mm and thickness 0.5 mm, which were bonded with the sample. The use of strain gauges allowed carrying out repeated check of correctness of their installation if we obtained doubtful results. If it was necessary, we could repeat the tests.

Every sample was tested by sixfold loading and unloading (partial asymmetric cycle of compression) with measurement of deformations in the process of loading from lower limit of tension, equal to 10% relative limit of proportionality, to upper limit of tension, which did not exceed 70% relative limit of proportionality during compression.

Relative limit of proportionality was determined with using prism samples with size 20x20x30 mm and chart "step of loading – difference of whole deformation in the step limit". Its value was determined as tension, conforming to the chart point of the straight-line transformation to curved-line.
Time of loading and unloading of the samples was accepted as constant and equal to 1.5 min.
The average arithmetic value of tension was determined using the recent three records of each strain gauge separately for upper and lower limits of tension. Then, absolute difference between those values and, finally, the average arithmetic value of absolute deformation of all tested samples were determined. Ratio between the average arithmetic value of absolute deformation and base of measurement is relative deformation. Coefficients of crosswise deformation were determined by dividing crosswise absolute or relative deformation by relevant lengthwise deformation.

III. Results and discussion

The results of the strength tests of the bakelite plywood standard samples with γ=978-1055 kg/m^3, which are used in real construction, are shown in table 1.

Table 1. Results of the strength tests of the bakelite plywood samples

Parameters	Number of tested samples	Average strength, MPa	Minimum strength, MPa	Maximum strength, MPa
Tensile strength along the fibers	12	99.1	75.7	133.5
Bending strength across the fibers	9	130.5	107.5	147.5
Bending strength along the fibers	10	168.9	123.4	187

Note: humidity of the samples is 7-8%.

Physical-mechanical characteristics even the same sample can fluctuate. The average values of some characteristics of the tested plywood are the following: humidity – 7.3%, volume weight – 1010 kg/m^2, tensile strength lengthwise the fibers – 99 MPa.
Relative limit of proportionality for the samples (fig. 2, a) was 78.7 MPa, for the samples (fig. 2, c) – 18.7 MPa. We could not find relative limit of proportionality for the samples (fig. 2, b) in explicit form using the above methodology. The lower and upper relative limits of proportionality were accepted equal to 1.3 MPa and 5 MPa for those samples.

The results of the tests and the main statistical parameters are shown in table 2. The statistical parameters are the following: n – number of the tested samples; M – average arithmetic value of relevant technical constant (for modulus of elasticity in MPa); σ – average quadratic deviation (for modulus of elasticity in MPa); m – average error of the average quadratic deviation (for modulus of elasticity in MPa); υ – coefficient of variability, %; ρ – parameter of accuracy, %.
The test results of samples with size 30x30x90 mm and values of the elasticity modulus (E_1) for those samples are also shown in table 2. Values, obtained on the samples with length 120 mm and 90 mm, are almost equal. It proves theoretical speculation to use the samples with ratio length and width not less than three.

Table 2. Results of the tests of bakelite plywood samples and the main statistical parameters

Parameters	n	M	σ	m	υ, %	ρ, %
Samples with size 30x30x120 mm						
E_1	5	14660	383	171.4	2.6	1.2
E_3	5	752.8	33.1	14.8	4.4	2
G_{13}	5	661.6	218	9.75	3.5	1.6
υ_{13}	5	0.1842	0.0159	0.00715	8.6	3.9
υ_{12}	5	0.2583	0.0143	0.00642	5.6	2.5
Samples with size 30x30x90 mm						
E_1	5	14570	316.2	141.4	2.2	1

Thus, the obtained technical constants of 9-layers bakelite plywood with thickness of 10 mm are the following: E_1=14700 MPa, E_3=750 MPa, G_{13}=620 MPa, υ_{12}=0.26, υ_{13}=0.18.
These technical constants can be used in practical calculations. For example, maximum tension of shear in the overlapping adhesive joints of anisotropic sheers with the same thickness under condition $l/\delta \geq 12\pi\theta_2$ is determined by equation (2).

$$\tau_{xy} = \frac{\theta_1}{\pi}\frac{\theta_2(3\kappa+1)}{(\theta_1-\theta_2)}\ln\left(\frac{\theta_2}{\theta_1}\right)\frac{N}{\delta} \quad (2)$$

where N – stretching tension for width of bonding; δ – thickness of bonded sheets; l – bonding length; θ_1 and θ_2 – parameters, characterizing elastic properties of orthotropic material and determined by using E_1, E_3, G_{13} and υ_{13}; k – coefficient, characterizing the change of bending moment for the bonding edge depending on bending stiffness of free tips of bonded sheets (L) and thickened part of bonding length.

Values θ_1 and θ_2 are equal to 1.071 and 0.211 according to the obtained technical constants of bakelite plywood (table 2). Therefore, equation (2) is valid if $l/\delta \geq 18_2$.
If we accept relative lengths L/δ and l/δ equal to 25 and 20 respectively, and stretching tension (N) equal to 2.7 kN, value (k) will be 0.276 and maximum stretching tension under the sheet thickness of 1 cm will be determined according to formula (3).

$$\tau_{xy} = 0.136(3\kappa + 1)\frac{N}{\delta} = 0.243\frac{N}{\delta} \qquad (3)$$

In this case, τ_{xy} is equal to 656 N/cm^2. The average stretching tension under the above size of bonding is equal to 135 N/cm^2 and coefficient of concentration of the shear tension is equal to 656/135=4.7. Stretching tension N=2.7 kN is about 70% value of destructive tension in the adhesive joint of bakelite plywood. It was determined using the above samples.

IV. Conclusion

Analysis of technical characteristics of bakelite plywood testifies to its certain advantages as constructional material. It can be widely used in civil engineering, replacing materials, such as steel and reinforced concrete, for different constructions.

The research results of physical-mechanical properties of bakelite plywood as orthotropic material can be used for design of sheet structures. They are necessary for practical calculations of tensions in the adhesive joints by methods of elastic theory of anisotropic materials.

The possibility of using the obtained research results for practical calculations is shown on the example of the overlapping adhesive joint.

V. Acknowledgement

This research work was supported by the Ministry of Education and Science of the Russian Federation (Agreement No. 02.A03.21.0008).

References

I. Aicher S., Hirsch M., Christian Z. (2016) Hybrid cross-laminated timber plates with beech wood cross-layers. Construction and Building Materials, vol. 124: 1007-1018.

II. Aydin I. (2004) Activation of wood surfaces for glue bonds by mechanical pre-treatment and its effects on some properties of veneer surfaces and plywood panels. Applied Surface Science, vol. 233: 268-274.

III. Bekhta P., Hiziroglu S., Shepelyuk O. (2009) Properties of plywood manufactured from compressed veneer as building material. Materials & Design, vol. 30(4): 947-953.

IV. Candan Z., Akbulut T. (2014) Nano-engineered plywood panels: Performance properties. Composites Part B: Engineering, vol. 64: 155-161.

V. Demirkir C., Özsahin S., Aydin I., Colakoglu G. (2013) Optimization of some panel manufacturing parameters for the best bonding strength of plywood. International Journal of Adhesion and Adhesives, vol. 46: 14-20.

VI. Fang L., Chang L., Guo W., Chen Y., Wang Z. (2014) Influence of silane surface modification of veneer on interfacial adhesion of wood–plastic plywood. Applied Surface Science, vol. 288: 682-689.

VII. Frolovs G., Rocens K., Janis S. (2017) Shear and Tensile Strength of Narrow Glued Joint Depending on the Grain Direction of Plywood Plies. Procedia Engineering, vol. 172: 292-299.

VIII. Khasanshin R.R., Safin R.R., Razumov E.Y. (2016) High Temperature Treatment of Birch Plywood in the Sparse Environment for the Creation of a Waterproof Construction Veneer. Procedia Engineering, vol. 150: 1541-1546.

IX. Kim J., Park D., Lee C., Park K., Lee J. (2015) Effects of cryogenic thermal cycle and immersion on the mechanical characteristics of phenol-resin bonded plywood. Cryogenics, vol. 72(1): 90-102.

X. Koroteev D.D., Boytemirov F.A., Stashevskaya N.A. (2017) The strength research of the adhesive joints of sheet structures. Journal of Fundamental and Applied Sciences, vol. 9(7S): 414-424.

XI. Lei H., Du G., Wu Z., Xi X., Dong Z. (2014) Cross-linked soy-based wood adhesives for plywood. International Journal of Adhesion and Adhesives, vol. 50: 199-203.

XII. Li W., Bulcke J., Mannes D., Lehmann E., Windt I., Dierick M., Acker J. (2014) Impact of internal structure on water-resistance of plywood studied using neutron radiography and X-ray tomography. Construction and Building Materials, vol. 73: 171-179.

XIII. Lokaj A., Vavrusova K. (2017) Longitudinal bonded joints of timber beams using plywood and LVL plates. Procedia Structural Integrity, vol. 5: 1363-1369.

XIV. Luo J., Li X., Zhang H., Gao Q., Li J. (2016) Properties of a soybean meal-based plywood adhesive modified by a commercial epoxy resin. International Journal of Adhesion and Adhesives, vol. 71: 99-104.

XV. Moubarik A., Pizzi A., Allal A., Charrier F., Charrier B. (2009) Cornstarch and tannin in phenol–formaldehyde resins for plywood production. Industrial Crops and Products, vol. 30(2): 188-193.

XVI. Muttil N., Ghanta Ravichandra, Bigger S.W. Thorpe G.R., Dorbha Shailaja, Swadesh Kumar Singh (2014) Comparative Study of Bond Strength of Formaldehyde and Soya based Adhesive in Wood Fiber Plywood. Procedia Materials Science, vol.6: 2-9.

XVII. Tan H., Zhang Y., Weng X. (2011) Preparation of the Plywood Using Starch-based Adhesives Modified with blocked isocyanates. Procedia Engineering, vol. 15: 1171-1175.

XVIII. Tang L., Zhang Z., Qi J., Zhao J., Feng Y. (2011) The preparation and application of a new formaldehyde-free adhesive for plywood. International Journal of Adhesion and Adhesives, vol. 31(6): 507-512.

XIX. Toksoy D., Çolakoğlu G., Aydin I., Çolak S., Demirkir C. (2006) Technological and economic comparison of the usage of beech and alder wood in plywood and laminated veneer lumber manufacturing. Building and Environment, vol. 41(7): 872-876.

XX. Windt I., Li W., Bulcke J., Acker J. (2018) Classification of uncoated plywood based on moisture dynamics. Construction and Building Materials, vol. 158: 814-822.

XXI. Yoshihara H. (2009) Edgewise shear modulus of plywood measured by square-plate twist and beam flexure methods. Construction and Building Materials, vol. 23(12): 3537-3545.

XXII. Zhou J., Zhao W., Tang K., Peng W. (2016) Seismic performance of square, thin-walled steel tube/bamboo plywood composite hollow columns with binding bars. Soil Dynamics and Earthquake Engineering, vol. 89: 152-162.