Magazine of Civil Engineering

ISSN 2712-8172

journal homepage: http://engstroy.spbstu.ru/

DOI: 10.34910/MCE.105.6

Resistance to temperature and humidity changes of construction plywood and thermal-insulation boards

A.A. Fedotov , T.N. Vahnina, I.V. Susoeva*

Kostroma State University, Kostroma, Russia

**E-mail: i.susoeva@yandex.ru*

Keywords: wood composites, phenol-formaldehyde binder, modification, structure, temperature, humidity, strength

Abstract. Plywood and thermal-insulation boards with phenol-formaldehyde binder (PF), like other composites for construction purposes, must have long-term strength with changing temperature and humidity. The insufficient degree of curing of the phenol-formaldehyde binder reduces the hydrolytic stability of the material. The aim of the study is to increase the long-term strength of materials when exposed to changes in temperature and humidity by improving the structure formation of composites with the introduction of modifying additives in the binder. In the work, the method of cyclic testing of materials “soaking – freezing – thawing – drying” was used. After each cycle, the strength of the samples was determined. Nine modifying additives to the phenol-formaldehyde binder were used – hydrogen peroxide, metal salts, sulfosalicylic acid, dimethylglyoxime. The proportion of additives varied from 0.5 to 1.5 %. Graphic dependences of changes in the strength of PF plywood and thermal-insulation boards from plant waste after cyclic tests are given. Materials on a modified binder have long-term resistance to variable temperature and humidity effects. Plywood on a phenol-formaldehyde binder with the addition of 0.5 % sulfosalicylic acid has, after 15 test cycles, a 2.8 times higher residual strength compared to plywood on an unmodified binder. Thermal-insulation composites from plant waste on a modified binder after cyclic tests have a strength of 9 % higher than plates on an unmodified binder.

1. Introduction

In the work, the ability of plywood and thermal-insulation boards with a phenol-formaldehyde binder to maintain long-term strength under temperature-humidity changes was studied. PF plywood and other composites based on lignocellulosic fillers and a thermosetting binder for use in construction should have increased water resistance and long-term performance under conditions of changes in temperature and humidity. Hot cured phenolic adhesives have high water resistance, but it can only be achieved at a sufficiently high pressing temperature. The manufacture of materials at low temperatures does not allow the formation of a hydrolytically stable binder, this leads to a decrease in the strength of the composites.

According to Sameer F. Hamad and colleagues, the necessary degree crosslinking of the phenol-formaldehyde oligomer can be achieved only by prolonged heating at high temperature, which is uneconomical [1].

It is necessary to reduce the pressing temperature to increase the efficiency of the production of plywood and boards on a phenolic binder. However, it is not only reduces the degree cure of the phenol formaldehyde binder. According to H.D. Dibaba, in the process of curing the phenolic binder, the yield of low molecular weight polycondensation products is difficult, which creates a porous structure of the polymer matrix [2].

As a result, the structure of the cured phenolic polymer is weakened [3]. Moisture falling into the adhesive layer at the boundary of the polymer and veneer or fine-grained filler causes moisture stress. When used as building materials, plywood and boards are affected by variable factors: moisture, freezing, heating, etc. The result is a decrease in the strength and water resistance of the material.

Fedotov, A.A., Vahnina, T.N., Susoeva, I.V. Resistance to temperature and humidity changes of construction plywood and thermal-insulation boards. Magazine of Civil Engineering. 2021. 105(5). Article No. 10506. DOI: 10.34910/MCE.105.6

With regard to PF plywood used as multi-turn formwork, a decrease in the long-term resistance of plywood will lead to non-compliance with the requirements of regulatory documents (Russian standard 34329–2017 Formwork).

The long-term resistance of PF plywood and other building composites based on plant fillers and phenol formaldehyde binder depends on the strength of the binder. Wood and other plant fillers are also affected by the processes of freezing, thawing, and drying [4–8].

During freezing, the volume of water inside the lumen of plant cells increases. Pressure on cell walls can cause microcracks in the material [9, 10].

The need to make a rational scientific and technological decision when choosing factors for the production of plywood and heat-insulating boards with phenol-formaldehyde binders led to the goal of this study. The study aims to ensure the long-term strength of the composites when exposed to changes in temperature and humidity by improving the structure formation of the material with the introduction of modifying additives in the binder.

To predict changes in the strength of wood-adhesive composites for construction purposes, such as plywood and slabs, methods of full-scale tests or accelerated cyclic methods can be used. Field test methods are informative and accurate. However, their disadvantages include a significant time frame for research. The complexity and duration of field tests reduces the efficiency of decision-making on the choice of technological effects on the material. Therefore, in world and domestic research practice, accelerated cyclic tests are more often used, which make it possible to evaluate the performance of the material after temperature and humidity effects.

A significant part of research in the world is aimed at studying the effect of freezing-thawing and freezing cycles on the mechanical properties of wood-plastic composites [11–16].

The effect of freezing and heat treatment cycles on the properties of plywood and other wood composites is not well understood.

A method for assessing the durability of wood-adhesive compositions was developed by V.M. Khrulev and A. S. Freidin. To assess the weather resistance of glued wood and board materials, a cyclic test regime was proposed, which included the presence of samples in water for 5 hours and drying at 70 °C for 24 hours. Russian standard 17580 (as amended in 1972) was developed in the development of studies.

Cyclic methods are applicable to the assessment of structural adhesive joints for wood-based building materials [17, 18]. The results of cyclic tests allow us to evaluate the resistance of the material to changes in temperature and humidity during operation.

2. Methods

Effect of modifying additives to the phenol formaldehyde binder (PF) on the PF-3014 resin (Russian standard 20907–2016) on the strength for shearing plywood FSF was investigated in this work (Table 1). Addition of each modifier ranged from 0.5 to 1.5 % by weight of the binder (in increments of 0.5 %).

Effect of the addition of sulfosalicylic acid to the PF on the strength under static bending of soft thermal-insulating boards of the wet method of production from wood waste and flax spinning waste compared with the dynamics of the change in the value of particle boards (PB) [19] are also presented. Thermal-insulating boards were made with an average density of 275 kg/m^3, and the average density of particle board was 800 kg/m^3. Samples of thermal-insulating boards were dried at 100 °C to a moisture content of 8±1 %, the particle boards were pressed at a temperature of 170 °C, a specific pressure of 2.6 MPa.

Table 1. Additives used to modify PF in the manufacture of PF plywood.

Modifier view	Chemical formula
Hydrogen peroxide (3 % aqueous solution)	H_2O_2
Zinc sulfate eight-water (aqueous solution)	$ZnSO_4 \cdot 8\ H_2O$
Iron ammonium alum (aqueous solution)	$NH_4Fe(SO_4)_2 \cdot 12H_2O$
Anhydrous magnesium chloride (aqueous solution)	$MgCl_2$
Ferric chloride hexahydrate (aqueous solution)	$Fe\ Cl_3 \cdot 6\ H_2O$
Aluminum chloride hexahydrate (aqueous solution)	$AlCl_3 \cdot 6\ H_2O$
Dimethylglyoxime (in dry form)	$C_4H_8N_2O_2$
Aluminum sulphate eighteen-water (aqueous solution)	$Al_2(SO_4)_3 \cdot 18H_2O$
Sulfosalicylic acid two-water (aqueous solution)	$C_7H_6O_6S \cdot 2\ H_2O$

Five-layer plywood was made on the basis of peeled birch veneer with a nominal thickness of 1.5 mm (Russian standard 99–2016). The veneer was pre-dried to a moisture content of (7±1) %. After forming the package and applying the binder, hot pressing was performed in a P100–400 laboratory hydraulic press with the following constant factors: pressing temperature – 120 ºC; pressing time – 5 min; specific pressing pressure – 1.6 MPa; binder consumption – 100 g/m^2. Manufactured plywood was cooled for 24 hours, then cut into samples for testing on shear strength.

For testing the strength of the samples used tensile testing machine R-5 (Russian standard 28840). Adaptation to a testing machine with wedge grippers was used to determine the strength of plywood during chipping. The arithmetic average of five duplicate experiments was taken as the test result.

According to the standard method of cyclic testing of material [18] one cycle of temperature and humidity effects on the samples included the following operations:

- the samples were placed in a vessel, loaded and poured for 20 hours with water having a temperature of (20±2) °C, so that they were covered with water by 2 ... 3 cm;
- wet samples extracted from water were transferred to a freezer and kept for 6 hours at a temperature of minus (20±2) °C;
- frozen samples extracted from the freezer were laid out on the rack and left to thaw for 16 hours at an air temperature of (20±2) °C;
- after thawing, the samples were placed in a drying chamber and kept for 6 hours at a temperature of (60±5) °C and air humidity (60 ... 75) %.

Samples of plywood passed 15 test cycles, samples of particle boards and thermal-insulating boards – 10 cycles.

3. *Results and Discussion*

The results of determining the strength of plywood during chipping after each of the test cycles are presented in Table 2 and in Fig. 1–3. Main results are presented in the figures due to the large volume of tests, in Table 2 shows the values for control samples without modification of the binder and for samples of plywood on a binder modified by the addition of sulfosalicylic acid.

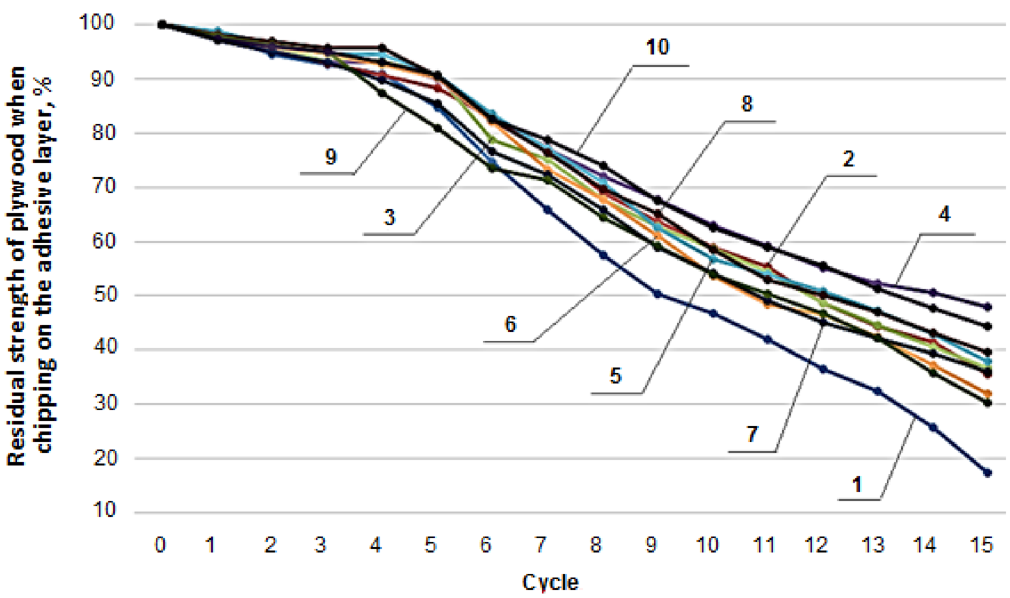

Figure 1. Dependences of residual shear strength, % plywood on a binder with the addition of 0.5 % modifier after cycles of temperature and humidity:
1 – control (without modifier); 2 – hydrogen peroxide (3 % aqueous solution);
3 – aluminum chloride hexahydrate (aqueous solution); 4 – sulfosalicylic acid two-water (aqueous solution); 5 – iron chloride III six-water (aqueous solution); 6 – anhydrous magnesium chloride (aqueous solution); 7 – iron ammonium alum (aqueous solution); 8 – zinc sulfate eight-water (aqueous solution); 9 – eighteen-aluminum sulphate (aqueous solution);
10 – dimethylglyoxime (in dry form).

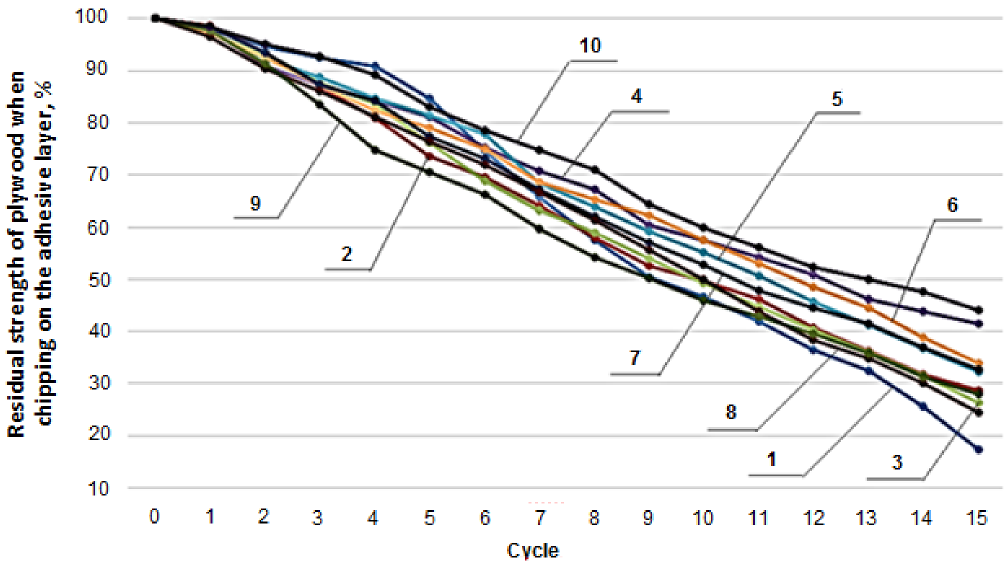

Figure 2. Dependences of residual shear strength, % plywood on a binder with the addition of 1 % modifier after cycles of temperature and humidity:
1 – control (without modifier); 2 – hydrogen peroxide (3 % aqueous solution); 3 – aluminum chloride hexahydrate (aqueous solution); 4 – sulfosalicylic acid two-water (aqueous solution); 5 – iron chloride III six-water (aqueous solution); 6 – anhydrous magnesium chloride (aqueous solution); 7 – iron ammonium alum (aqueous solution); 8 – zinc sulfate eight-water (aqueous solution); 9 – eighteen-aluminum sulphate (aqueous solution); 10 – dimethylglyoxime (in dry form).

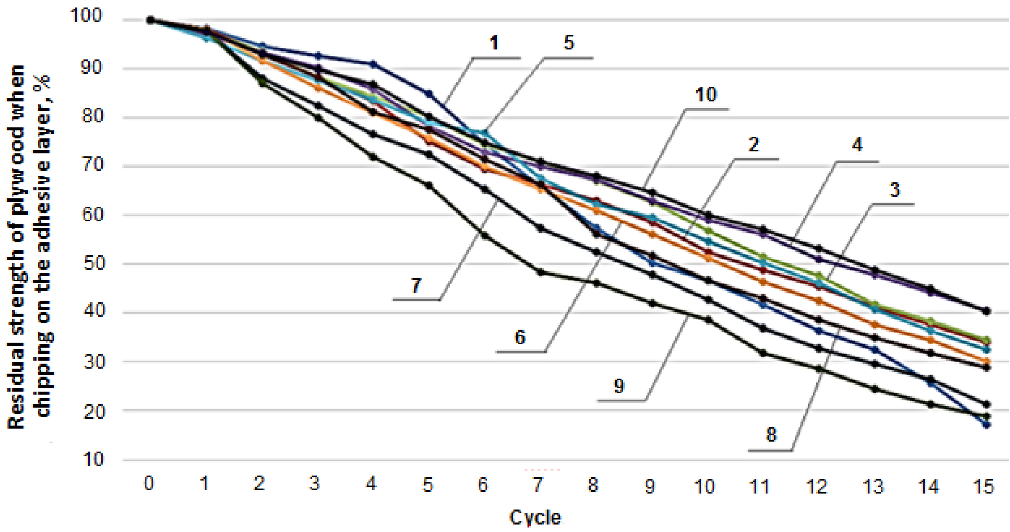

Figure 3. Dependences of residual tensile strength, % plywood on a binder with the addition of 1.5 % modifier after cycles of temperature and humidity:
1 – control (without modifier); 2 – hydrogen peroxide (3 % aqueous solution); 3 – aluminum chloride hexahydrate (aqueous solution); 4 – sulfosalicylic acid two-water (aqueous solution); 5 – iron chloride III six-water (aqueous solution); 6 – anhydrous magnesium chloride (aqueous solution); 7 – iron ammonium alum (aqueous solution); 8 – zinc sulfate eight-water (aqueous solution); 9 – eighteen-aluminum sulphate (aqueous solution); 10 – dimethylglyoxime (in dry form).

Table 2. Dynamics of changes in the strength of plywood chipping in cyclic tests (above the line for samples with a modifier, below the line for control).

Cycles	Shear strength, σ_{ss}, MPa	Residual strength,%
Before the test	2.79/2.96	–
0.5 % modifier additive		
1	2.71/2.90	97.25/98.10
2	2.65/2.80	94.98/94.59
3	2.60/2.74	93.19/92.57
4	2.60/2.69	93.19/90.88
5	2.51/2.51	89.96/84.80
6	2.29/2.21	82.08/74.66
7	2.15/1.95	77.06/65.88
8	2.01/1.70	72.04/57.43
9	1.89/1.49	67.74/50.34
10	1.76/1.38	63.08/46.62
11	1.65/1.24	59.14/41.89
12	1.54/1.08	55.20/36.49
13	1.46/0.96	52.33/32.43
14	1.41/0.76	50.54/25.68
15	1.34/0.51	48.03/17.23
1.0 % modifier additive		
1	3.12/2.90	98.06/98.10
2	2.89/2.80	90.88/94.59
3	2.78/2.74	87.42/92.57
4	2.68/2.69	84.28/90.88
5	2.58/2.51	81.13/84.80
6	2.39/2.21	75.16/74.66
7	2.25/1.95	70.75/65.88
8	2.14/1.70	67.30/57.43
9	1.92/1.49	60.38/50.34
10	1.83/1.38	57.55/46.62
11	1.72/1.24	54.09/41.89
12	1.62/1.08	50.94/36.49
13	1.47/0.96	46.23/32.43
14	1.39/0.76	43.71/25.68
15	1.32/0.51	41.51/17.23
1.5 % modifier additive		
1	2.87/2.90	96.83/98.10
2	2.76/2.80	93.24/94.59
3	2.67/2.74	90.20/92.57
4	2.54/2.69	85.81/90.88
5	2.32/2.51	78.38/84.80
6	2.16/2.21	72.97/74.66
7	2.07/1.95	69.93/65.88
8	1.99/1.70	67.23/57.43
9	1.86/1.49	62.84/50.34
10	1.75/1.38	59.12/46.62
11	1.66/1.24	56.08/41.89
12	1.51/1.08	51.01/36.49
13	1.42/0.96	47.97/32.43
14	1.31/0.76	44.26/25.68
15	1.20/0.51	40.54/17.23

Plywood on an unmodified phenol-formaldehyde binder after 15 test cycles has a residual strength of less than 20 %. The reason for this is the low degree of curing of the binder at a pressing temperature of 120 °C and the presence of microvoids in the cured binder. Water penetrates micropores during testing, freezes, evaporates, and causes hydrolytic destruction of the polymer.

One cannot disagree with G.A. Ormondroyd [20], that the adhesives used in the manufacture of wood composites have arguably the most influence on the composites properties. The adhesives influence all aspects of the composites, from their mechanical properties and their ability to perform in wet conditions.

With a share of modifier additives of 0.5 % by weight of the resin, plywood sulfosalicylic acid and dimethylglyoxime give the best resistance to variable temperature and humidity effects (Fig. 1). They create additional crosslinking units in the cured polymer network [21] and provide higher hydrolytic stability of the binder. With a share of modifier additives of 1 % and 1.5 %, sulfosalicylic acid and dimethylglyoxime also give the best results in increasing the residual strength of plywood after cyclic tests (Fig. 2).

Hydrogen peroxide, used by J. Sedliacik and colleagues in the study as a phenolic binder modifier [22], in small amounts (0.5 %), a positive effect on the spreadability of the binder during the veneering of veneer. Up to five test cycles, it positively affects the residual strength of plywood, however, with further temperature and humidity effects, the addition of hydrogen peroxide has a lesser effect on increasing the residual strength of plywood. Addition of hydrogen peroxide in an amount of 1 ... 1.5 % does not significantly affect the increase in the residual strength of plywood during cyclic tests.

Addition of iron, magnesium and aluminum chlorides on average increases the residual strength of plywood after cyclic tests, but their effect is less effective than for the addition of dimethylglyoxime and sulfosalicylic acid.

Despite the fact that aluminum salts are traditionally considered to be phenolic binder modifiers, aluminum sulfate showed the worst results when introduced into the adhesive composition. When the proportion of the additive is 1.5 %, the amount of aluminum sulfate becomes redundant, the residual strength of plywood with this modifier is lower than that of control samples.

The results of tests for static bending after cyclic effects of thermal-insulating boards with the addition of spinning waste of flax fiber and particle boards are presented in Table 3.

Table 3. Dynamics of changes in strength under static bending thermal-insulating boards and particle boards in cyclic tests (above the line for samples with a modifier, below the line for control).

Cycles	Thermal-insulating boards		Particle boards	
	Strength in static bending, σi, MPa	Residual strength, %	Strength in static bending, σi, MPa	Residual strength, %
Before the test	0.55/0.58		25.5	
1	0.53/0.57	96/98	21.1	82.5
2	0.53/0.56	96/97	18.3	71.5
3	0.52/0.53	94/91	16.0	62.9
4	0.51/0.52	93/90	13.2	51.6
5	0.49/0.51	89/88	10.5	41.0
6	0.47/0.50	85/86	7.9	31.3
7	0.47/0.48	85/84	6.0	23.5
8	0.41/0.43	74/75	4.7	18.5
9	0.32/0.40	58/70	4.3	16.8
10	0.26/0.32	47/56	3.5	13.7

The addition of sulfosalicylic acid in an amount of 0.5 % to the phenol-formaldehyde binder also increases the residual strength of soft thermal-insulating boards from wood waste and flax fiber spinning waste (Table 3). Low-density boards have a low value of strength under static bending, however, in comparison with more durable particle boards, thermal-insulating boards have a higher value of residual strength after cyclic tests. It should be noted that the modification of the phenolic binder with the addition of sulfosalicylic acid increases by 9 % the residual strength of the thermal-insulating boards after 10 test cycles, the residual strength index for these boards is four times higher than that of particle boards with an unmodified phenol-formaldehyde binder.

4. Conclusions

1. Plywood on a phenol formaldehyde binder with the addition of 0.5 % sulfosalicylic acid, manufactured at a pressing temperature that does not provide a high degree of curing of the binder, has

after 15 test cycles 2.8 times higher residual strength compared to plywood on an unmodified binder. This allows us to predict a longer service life of plywood during operation with changes in temperature and humidity.

2. Best results on increasing the residual strength of plywood with changes in temperature and humidity are provided by modifiers sulfosalicylic acid and dimethylglyoxime, added in an amount of 0.5 ... 1.5 % by weight of the phenolic binder.

3. Modification of the binder with sulfosalicylic acid for the production of soft thermal-insulating boards of the wet method production from wood waste and non-returnable waste spinning flax, allows to increase the residual strength of the material by 9 %.

4. Thus, the obtained experimental data make it possible to recommend the addition of dimethylglyoxime or sulfosalicylic acid as modifiers of the phenol formaldehyde binder for lignocellulosic materials, such as plywood and thermal-insulating boards. Modifiers will increase the residual strength of materials used under changing temperature and humidity conditions, and therefore, will increase the life of plywood and boards.

5. Acknowledgement

The study was financially supported by the Russian Federal Property Fund and the Kostroma Oblast Administration as part of a scientific project No. 19-43-440001.

References

1. Hamad, S.F., Farr, N., Fei, T. Optimizing size and distribution of voids in phenolic resins through the choice of catalyst types. Journal of Applied Polymer Science. [Online]. System requirements: Adobe Acrobat Reader. URL: https://doi.org/10.1002/app.48249 (date of application: 10.03. 2020).
2. Henock, D.D. Permeability barriers for composites ageing mechanisms and surface treatment of polymeric matrix composites under cyclic load. Materials Processing Technology. [Online]. System requirements: Adobe Acrobat Reader. URL: http:// www.theseus.fi (date of application: 10.03. 2020).
3. Fedotov, A.A., Vachnina, T.N., Kotikov, S.A. Improving strength indicators of fsf plywood by using modifiing additives to binding agent. Forestry Engineering Journal. 2020. 1. Pp. 124–135. DOI: 10.34220/issn.2222-7962/2020.1/13. (rus)
4. Ugolev, B.N., Galkin, V.P., Gorbacheva, G.A., Kalinina A.A. Frozen shrinkage of wood. Proceedings 6th International symposium IUFRO – TUZVO «Wood Strukture and Properties'10». Zvolen. Slovakia, 2010. Pp. 73–77.
5. Câmpean, M., Ispas, M., Porojan, M. Considerations on drying frozen spruce wood and effects upon its properties. 2008. Drying Technology. 26. Pp. 596–601.
6. Kärenlampi, P.P, Tynjälä, P., Ström, P. Phase transformations of wood cell wall water. Journal of Wood Science. 2005. 51. Pp. 118–123.
7. Green, D.W., Evans, J.W., Logan, J.D., Nelson, W.J. Adjusting modulus of elasticity of lumber for changes in temperature. Forest Products Journal. 1999. 49 (10). Pp. 82–94.
8. Mishiro, A. Effect of freezing treatments on the bending properties of wood. Bulletin of Tokyo University. 1990. 82. Pp. 177–189.
9. Ilic, J. Advantages of pre-freezing for reducing shrinkage-related degrade in eucaliptus: General considerations and review of lieterature. Wood Science and Technology. 1995. 29 (4). Pp. 277–285.
10. Szmutku, M.B., Câmpean, M., Sandu, A.V. Microstructure modifications induced in spruce wood by freezing. ProLigno. 2011b. 7 (4). Pp. 26–31.
11. Pilarski, J.M., Matuana, L.M. Durability of wood flour-plastic composites exposed to accelerated freeze-thaw cycling. Part I. Rigid PVC matrix. Journal of Vinyl and Additive Technology. 2005. 11(1). Pp. 1-8. DOI: 10.1002/vnl.20029
12. Wang, W.H., Morrell, J.J. Effects of moisture and temperature cycling on material properties of a wood/plastic composite. Forest Product Journal. 2005. 55 (10). Pp. 81–83.
13. Schildmeyer, A.J., Wolcott, M.P., Bender, D.A. Investigation of the temperature-dependent mechanical behavior of a polypropylene-pine composite. Journal of Materials in Civil Engineering. 2009. 21 (9). Pp. 460−466. DOI: 10.1061/(ASCE)0899-1561(2009)21:9(460)
14. Nadir, A., Songklod, J., Vallayuth, F., Piyawade, B. Effect of thermal treatment of wood-fiber on properties of flat-pressed wood plastic composites. Polymer Degradation and Stability. 2011. 96 (5). Pp. 818–822.
15. Xue, Y., Veazie, D., Glinsey, C., Wright, M., Rowell, R.M. Mechanical Properties of Wood Fiber Composites Under the Influence of Temperature and Humidity. [Online]. System requirements: Adobe Acrobat Reader. URL: https://www.researchgate.net/publication/237135869 (date of application: 10.03. 2020).
16. Franco, L.A.L., Graça, M.L.A., Silva, F.S. Interlaminar shear strength and fractographic evaluation with varying temperature and moisture content of thermoplastic composites. Applied Mechanics and Materials. 2005. 3–4. Pp. 179–184.
17. Russian standard 17580-82. Konstrukcii derevyannye kleenye. Metod opredeleniya stojkosti kleevyh soedinenij k ciklichnym temperaturno-vlazhnostnym vozdejstviyam [State standard specification. Wooden laminated structures. Method to determinate stability of glued joints against cyclic temperature-and humidity influences]. (rus)
18. Russian standard 33121-2014. Konstrukcii derevyannye kleenye. Metody opredeleniya stojkosti kleevyh soedinenij k temperaturno-vlazhnostnym vozdejstviyam [State standard specification. Glued timber structures. Methods for determining the resistance of glue joints to the temperature and humidity effects]. (rus)
19. Susoeva, I.V., Vakhnina, T.N., Titunin, A.A., Asatkina, J.A. The performance of composites from vegetable raw materials with changes in temperature and humidity. Magazine of Civil Engineering. 2017. 3(71). Pp. 39–50. DOI: 10.18720/MCE.71.5

20. Ormondroyd, G.A. Adhesives for wood composites. [Online]. System requirements: Adobe Acrobat Reader. URL: https://www.researchgate.net/publication/284172771_Adhesives_for_wood_composites (date of application: 10.03. 2020).
21. Vakhnina, T.N., Fedotov, A.A., Titunin, A.A., Susoeva, I.V. Vliyanie modifikatorov na vremya otverzhdeniya fenoloformal'degidnogo svyazuyushchego dlya pressovaniya fanery pri nizkotemperaturnom rezhime [Influence of modifiers on the curing time of the phenol formaldehyde binder for pressing panels at low temperature mode]. Forestry Engineering Journal. 2019. 4. Pp. 99–108. DOI: 10.34220/issn.2222-7962/2019.4/11. (rus)
22. Sedliacik, J., Bekhta, P., Potapova, O. Technology of low-temperature production of plywood bonded with modified phenol–formaldehyde resin. Wood research. 2010. 55(4). Pp. 124–130. https://www.researchgate.net/publication/267026018

Contacts:

Alexander Fedotov, aafedotoff@yandex.ru
Tatiana Vahnina, t_vachnina@mail.ru
Irina Susoeva, i.susoeva@yandex.ru