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ORIGINAL ARTICLE

Computation of durability of particle boards based on biobinders during thermal aging

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Abstract The change in the strength of particle boards made using nontoxic-modified residual brewer's yeast as a biobinder during thermal aging was studied. It was shown that the strength of the particle boards increased during the first 24 h when the boards were exposed to temperatures of + 50 and + 80 °C, and then the strength decreased. Through the approximation of the experimental results for the changes in strength during thermal aging using polynomial and power functions, the aging period (durability) of the particle boards under accelerated testing conditions was determined. The calculated values for the activation energy of the thermal degradation processes and the values of the actual (equivalent) operating temperature of the pressed products were used to calculate the durability of the wood composites under operating conditions. It was found that the estimated durability of particle boards made with brewer's yeast as a biobinder was 11 months and slightly lower than that of particle boards made with toxic synthetic resins.

Keywords Particle boards · Biobinding · Durability · Accelerated thermal aging method · Ultimate strength under static bending

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Introduction

Approximately 100 million m3 of ground waste from wood and other plants are produced annually in the woodworking and agricultural industries. Using these wastes as the main raw material for the production of wood-composite materials, particularly particle boards, preserves very large reserves of plant resources.

Particle boards, as well as building and finishing materials based on them, are traditionally widely used in the construction and furniture industry. In the production of particle boards, alcohol-soluble and water-soluble resins—materials that are capable of binding wood particles to each other under pressure and at elevated temperature—are used as binders. However, the particle boards produced by this technology release phenol, formaldehyde and a number of other toxic substances into the air during operation. The concentration of formaldehyde in residential premises equipped with furniture and construction structures containing particle boards may exceed the maximum permissible concentration (MPC) by 5–10 times. This is a major limitation on the increased use of particle boards in construction. Therefore, the reduction in the toxicity of particle boards is very relevant (Carll 1986; Carlborn et al. 2006; Li et al. 2005).

There are several main ways to reduce the toxicity of particle boards: applying an insulating layer of facing and

paint materials on the surface of the boards; modifying the binder; developing rational modes of pressing plates; processing finished particle boards or chips with substances that can form time-stable compounds with formaldehyde; and preliminary biological modification of wood waste by microorganisms and enzymes followed by pressing (Varankina et al. 2011; Idirs et al 2011; Kadimaliev et al 2001, 2004; Zhang et al 2011).

One of the most promising ways to solve the problem of particle board toxicity is to replace synthetic resins with environmentally safe and cheap biobinders, for example, adhesive compositions of natural origin. Thus, in previous works (Kadimaliev et al 2012, 2015; Novokuptsev 2017; Revin et al 2016a, 2016b) it was shown that yeast waste with appropriate modification, as well as microbial polysaccharides, acquires adhesive properties, and this waste can be used as an environmentally safe bioglue in the production of pressed materials from waste plant raw materials. The most important requirement that characterizes the quality and possibility of using wood composite materials in the construction and furniture industry is the ability to preserve the level of the elastic-strength properties in storage and operation conditions. Most particle boards have low stability regarding their properties over time. Under the influence of external factors, particle boards undergo aging processes that are expressed as changes in the chemical and physical structure and, as a result, the deterioration of the elastic strength and other operational properties (Manin et al. 1980; Pavlov 1982).

Predicting the durability of polymer building materials can be performed using two main methods: field tests at climate stations and accelerated laboratory tests. The first method takes into account all the operational factors affecting the material, but the duration of the tests is comparable to the service life of the material. The second method reduces the duration of the tests tens of times by determining the durability. The prediction methods used in this case are based on the principle of transforming the energy values of the external factors responsible for the aging and destruction of polymer materials into adequate laboratory modes that cause the same changes in the material as operation in real conditions. For a satisfactory prediction, it is necessary to determine simple and reliable relationships between the kinetic parameters of physical and chemical processes and the macro-properties of the material that determine its performance (Goichman et al. 1980). Much more interesting are artificial test techniques that reduce forecasting time (Goichman et al 1968; Griciute et al 2013; Masters et al. 1989).

The method of extrapolating the results of accelerated tests for long-term operation in real conditions takes into account only one determining factor in the environment, usually temperature—the method of accelerated thermal aging. The essence of this test lies in the fact that the rate of change in the properties of the material at an elevated temperature can be determined by extrapolation of the change in the same properties at the operating temperature of products made of the material (Boeva et al. 2014; Gonzalez et al. 1993; Griciute et al 2013; Koči et al 2012; Pavlo et al. 2003; Vidrina et al 2007).

In this case, the Arrhenius equation is used to describe the rate of the chemical reaction. To account for other factors, correction coefficients are introduced into this equation (Carpukhin 1980; Goichman et al 1968, 1980; Pavlov1982).

Such studies have not been carried out in relation to particle boards obtained with the use of biobinders. Because biobinders have shorter time stability regarding adhesive characteristics than synthetic resins, it can be assumed that particle boards based on biobinders will have less durability and resistance to climatic influences than traditional particle boards.

The purpose of the present work was to study the effects of increased temperature and duration on the elastic-strength characteristics of samples of particle boards with bioglue (PB-BG) and particle boards without bioglue (PB-wBG) as well as to predict their possible service life in heated rooms.

Materials and methods

Pine sawdust with a particle size of 3–5 mm and bioglue as a binder was used for the production of experimental particle boards (PB-BG). Bioglue was obtained from residual brewer's yeast as described in previous works (Kadimaliev et al 2012, 2015).

The viscosity of the biobinder was adjusted by dilution with boiling water. To obtain a press mass, sawdust was mixed with a biobinder by the extrusion method (at a ratio of 100 g of sawdust to 70 ml of bioglue) and dried in a thermostat at 60 °C with a humidity of 6–8%.

Seventy-five grams of obtained press mass was loaded into a mold with a size of 150 × 50 × 10 mm. After cold premolding, hot pressing was conducted on a Gotech-7014-H press (Gotech Testing Machines Inc., Taiwan—United States) at a temperature of 160–180 °C and pressure of 3 to 5 MPa per 1 mm of thickness of particle board. The pressing time was 30 s per millimeter of thickness of particle board (Kadimaliev et al 2012, 2015; Novokuptsev 2017; Revin et al 2016a, 2016b). The obtained particle boards made in this way were cooled to room temperature and tested for bending strength in accordance with Russian State Standard 10,635–88 (1898) Woodchip boards. Methods for determining the tensile strength and flexural modulus on a GotechAI-7000 M universal testing machine.

Accelerated thermal aging of the obtained particle boards was performed in a Gotech-7017-NM (ASTM-D2436) furnace at temperatures of 50 and 80 °C for 12, 24, 48, 96, 144, and 192 h of conditioning at 50–60% humidity. After conditioning, the samples were kept for 1 day at room temperature, after which the static bending strength was determined. Particle boards made without biobinder were used as control samples.

Calculations for predicting the durability of the material were performed in accordance with Russian State Standard 9.707–81 (1990) Unified corrosion and aging protection system. Polymeric materials. Accelerated climate ageing testing methods (Khrulev et al. 1977).

All the tests were performed in fivefold repetition and statistically processed using Microsoft Excel.

Results and discussion

The results of the strength tests on the particle boards subjected to thermal aging at a temperature of 22 ± 2 °C are presented in Table 1.

The results of the experiment show that conditioning of plate samples at room temperature has virtually no effect on the strength of the obtained samples. Based on this result, we can conclude that under normal conditions, the service life of products from the developed biocomposites will be sufficient for their practical use.

The next stage of the experiment was to study the effect of temperature on the bending strength of the obtained particle boards without or with the addition of bioglue based on modified brewer's yeast. In this regard, aging of the biocomposite material was performed under more severe temperature conditions. Figure 1 shows the changes with time in the relative strength of samples of PB-BG and PB-wBG at temperatures of 50 °C (a) and 80 °C (b).

The results of the experiment show that in the initial period (up to 24 h of exposure) at a temperature of 50 °C (Fig. 1a), there was a noticeable increase in strength in both types of particle boards. Additionally, the particle boards obtained with bioglue had higher strength in the range of 12–48 h of thermal exposure than the particle boards obtained without bioglue.

After 24 h of exposure, the strength of both samples began to decrease, but the strength of the biocomposites (PB-BG) was significantly higher.

The process of decomposition of both filler (sawdust) and binder (bioglue) is likely to begin when the samples are held at temperature for a long time. Additionally, the thermal degradation of the biobinder proceeds at a higher rate than the destruction of lignin fragments and other components of sawdust. Moreover, despite the higher rate of aging of the sample with bioglue, its strength remains at a high level.

Figure 1b shows the results of thermal aging of samples at a temperature of 80 °C with the same time intervals, followed by the determination of the static bending strength.

It follows from the obtained data that at an aging temperature of 80 °C, processes are occurring similar to those occurring during aging at a temperature of 50 °C. The particle boards obtained using bioglue were significantly stronger than particle boards pressed without biobinders in terms of their strength during thermal aging. However, the rate of decrease in the relative strength (after 12 h of exposure) in both samples was significantly higher at 80 °C than at the aging temperature of 50 °C. The decrease in relative strength in this case was 83% for the particle boards obtained with bioglue and 75% for the particle boards obtained without bioglue.

Thus, increasing the temperature of thermal aging to 80 °C resulted in acceleration the thermal degradation processes of the particle boards.

Important in the study of materials by accelerated thermal aging methods is the prediction of the duration of the possible use of biocomposite products. To determine their durability, the experimental results of the bending strength of the samples were approximated by polynomial and power functions.

To determine the durability of polymers in accordance with Russian State Standard 9.707–81 (1990) Unified corrosion and aging protection system. Polymeric materials. Accelerated climate ageing testing methods, the Arrhenius equation was used, based on which the durability of the material in real operating conditions can be calculated using a well-known Eq. (1):

$$t_{\text{operation}} = t_{\text{test}} \exp[E/R(T_{\text{test}}^{-1} - T_{\text{operation}}^{-1})] \quad (1)$$

Table 1 Measures of bending strength of particle boards

The duration of exposure of samples, hs						
Type of material	12	24	48	96	144	192
Static bending strength, MPa						
PB-wBG	8,1 ± 0,5	8,1 ± 0,3	8,0 ± 0,1	7,9 ± 0,2	8,0 ± 0,4	7,8 ± 0,2
PB-BG	18,8 ± 0,5	18,8 ± 0,1	18,6 ± 0,2	18,9 ± 0,3	18,7 ± 0,1	18,8 ± 0,5

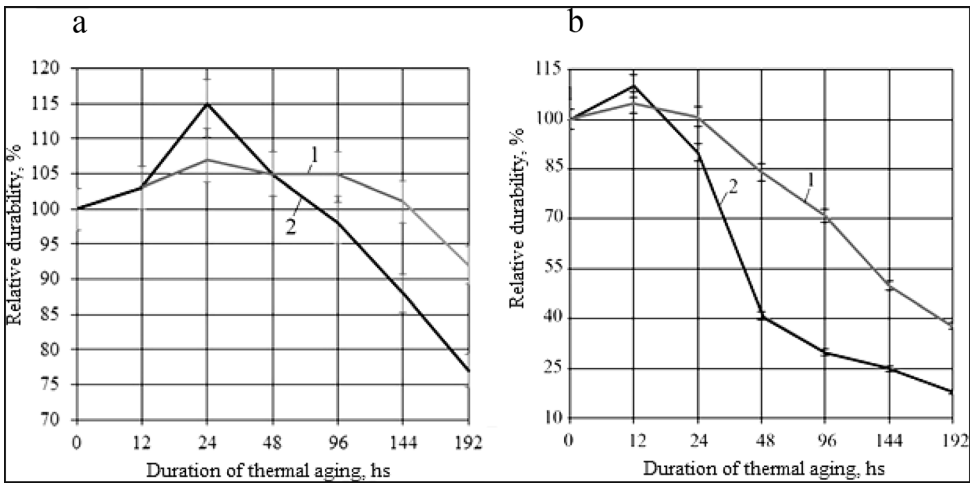

Fig. 1 Change in the relative bending strength of PB-wBG (1) and PB-BG (2) during the time of thermal aging at temperatures of + 50 °C (**a**) and + 80 °C (**b**)

where $t_{operation}$ and t_{test}—the durability of the material under operating and testing conditions, respectively, hours; E—activation energy of thermodestruction and decomposition processes, J/(mol); R = 8,314—universal gas constant, J/(mol•K).

Figure 2 shows the experimental values and trends of the dependences of the strength of the PB-BG (a) and PB-wBG (b) plates during bending with the duration of thermal aging at temperatures of 50 and 80 °C.

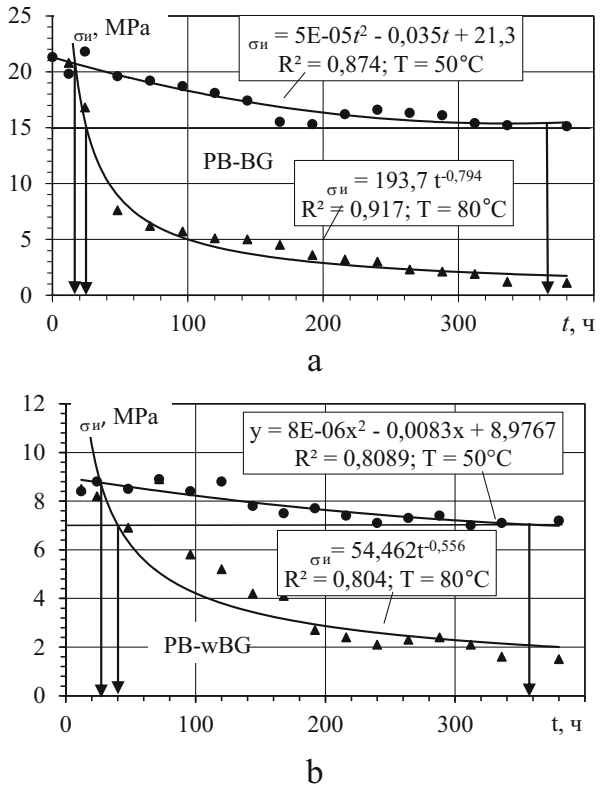

Fig. 2 Correlation of the bending strength of the PB-BG (**a**) and PB-wBG (**b**) from duration of thermal aging at temperatures of + 50 °C and + 80 °C

The value of the activation energy E in our case can be calculated based on the results obtained (Fig. 2) using Eq. (2):

$$E = \frac{R \ln(t_1/t_2)}{T_1^{-1} - T_2^{-2}} \quad (2)$$

According to the trend equations (Fig. 2a), the durability of thermal aging t_1 at a temperature T_1 = 353 K, during which the strength of the particle boards decreased by 6,3 MPa (from 21,3 to 15 MPa), is 8 h.

The durability t_2 at a temperature of T_2 = 323 K, during which the strength of the particle boards decreased by the same value, is 363 h.

For the particle boards produced without bioglue (Fig. 2b), the durability t_1 of thermal aging at a temperature T_1 = 353 K, during which the strength of the particle board decreased by 2 MPa (from 9 to 7 MPa), is 15 h. The durability t_2 at a temperature T_2 = 323 K, during which the strength of the plate decreased by the same value, is 355 h.

The values of the activation energy E calculated using Eq. (2) were 120,5 kJ/mol for PB-BG and 100 kJ/mol for PB-wBG.

Figure 3 shows the dependence of the operating resource $t_{operation}$ of PB-BG (a) and PB-wBG (b) on the operating temperature calculated according to Eq. (1), based on conditions of strength reduction by 10% (1) and 20% (2).

It is known that the main chemical component of wood is cellulose, which is the structural basis of plant cells. In turn, cellulose is bound by hydrogen bonds with lignin macromolecules, forming a lignocarbon complex that can comprise up to 80% of the wood mass.

With aging, both the structure and chemical composition of wood change (Ganne-Chedeville et al 2011; Khrulev et al. 1983; Kiseloyva 2003; Martynov et al. 1984).

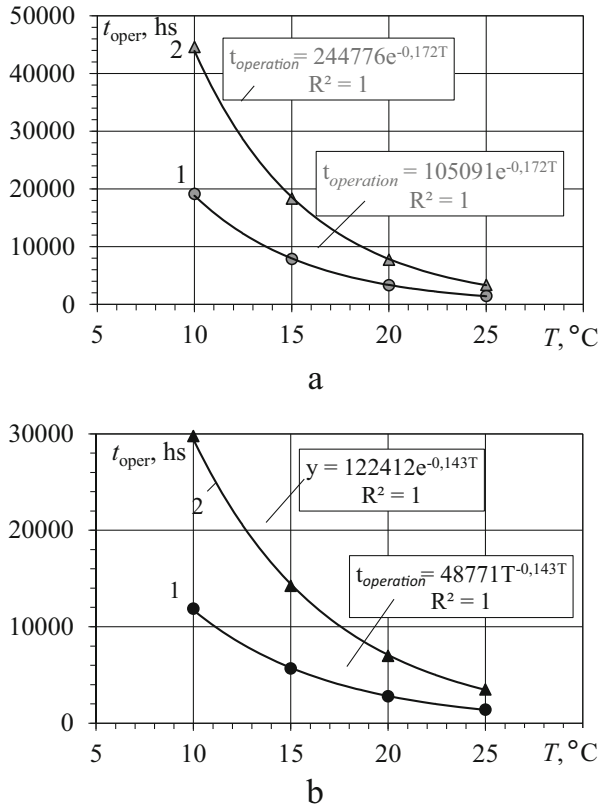

Fig. 3 Dependence of the durability of PB-BG (**a**) and PB-wBG (**b**) on the temperature of operation under conditions of strength reduction by 10% (1) and 20% (2)

An increase in temperature contributes to the activation of aging processes, and the intensity of the changes in the structure and chemical composition of wood depends only on the temperature. The temperature region in which such transformations occur is called the "aging region," which is associated with the glass-transition temperature and other relaxation transitions that are characteristic of this polymer. As a result of ongoing physical processes, the configuration (conformational set) of the macromolecular chains and their supramolecular structure is changed. The time factor plays a crucial role in this case (Pavlov 1982).

In our case, a slight increase in strength in the first 24 h of thermal aging (Fig. 1) may be due to the condensation of wood components, such as lignin, forming a very strong three-dimensional grid (Bazarnova et al 1997a, 1997b; Manin et al. 1980; Pavlov 1982; Vidrina et al 2007).

Additionally, it was found that in the samples without a biobinder, the increase in strength was less significant. This probably occurs because at elevated temperatures, the processes of adhesive interactions between the glue and wood particles intensify in the initial moments.

A work by Kiselyova (2003) examined the bond disruption in composites under prolonged exposure to elevated temperature by means of kinetic swelling curves and calculation of the activation energy from the curves. Analyzing the results of the calculations, the authors concluded that the binder plays a decisive role in the swelling processes and that the increase in activation energy with increasing duration of aging is caused by the destruction of the chemical bonds of the binder. We have previously shown (Kadimaliev et al 2012, 2015) that the main component that determines the adhesive properties of the bioadhesive is proteins. Longer exposure to elevated temperature leads to the denaturation of the protein component of the bioglue, resulting in a reduced intensity of adhesion and cohesive interaction with the lignocarbon complex of wood.

Calculations show (Fig. 3) that the durabilities of PB-BG and PB-wBG calculated by thermal aging differ slightly. For PB-BG, the durabilities at a temperature of 20 °C for the conditions of strength reduction by 10 and 20% are 5 and 11 months, respectively. For PB-wBG, these values are 4 and 10 months, respectively. From the obtained data, it follows that the addition of a biobinder practically does not affect the durability. However, the durability of the resulting particle boards is high, albeit slightly lower than that of particle boards produced using phenol–formaldehyde resins (Vidrina et al 2007).

Thus, particle boards produced using a nontoxic biobinder based on modified brewer's yeast are less durable than particle boards produced using toxic phenol–formaldehyde resins. However, such particle boards do not emit toxic compounds into the environment, and there are no problems with the disposal of materials that have failed during operation. Particle boards obtained with the use of biobinders and products made from such particle boards can be recommended for use in closed rooms with normal humidity. This is especially important for residential buildings and educational and medical institutions that are subject to strict sanitary and hygienic requirements.

Conclusions

During the heat treatment of particle boards without biobinders (PB-wBG) and particle boards with biobinders (PB-BG) at temperatures of 50 and 80 °C in the first 24 h, there were increases in the relative strength of particle boards under bending of 8 and 15%, respectively. After 24 h of exposure, the relative strength of both samples began to decrease, but the relative strength of the biocomposite (PB-BG) was significantly higher. The estimated durability of PB-BG produced with nontoxic biobinders was 11 months and slightly lower than that of the particle boards produced with toxic phenol–formaldehyde resins. Particle boards produced with nontoxic biobinders can be used in closed rooms with normal humidity.

Declaration

Conflict of interest The authors declare that they have no conflict of interest.

References

Bazarnova NG, Galochkin AI, Krestyannikov VS (1997a) Urea influence on the properties of pressed materials made of wood subjected to a hydrothermal treatment. Chem Plant Raw Mater 2:22–30

Bazarnova NG, Galochkin AI, Krestyannikov VS (1997b) Effect of wood hydrothermal treatment on properties of wood pressed materials. Chem Plant Raw Mater 2:11–16

Boeva R, Radtva G (2014) Compensation effects in the kinetics of thermal aging of semi chemical pulp. J Chem Technol Metall 49(6):585–593

Carlborn KLM, Matuana LM (2006) Influence of processing conditions and material compositions on the performance of formaldehyde-free wood-based composites. Polym Compos 27:599–607. https://doi.org/10.1002/pc.20175

Carll C (1986) Wood particle board and flake board: types, grades, and uses; Department of Agriculture, Forest Service, Forest Products Laboratory, U.S.

Carpukhin ON (1980) Determining the lifetime of a polymer material as a physical and chemical problem. Usp Khim 49(8):1523–1553

Ganne-Chedeville C, Jaaskelainen A-S, Froidevaux J et al (2011) Natural and artificial ageing of spruce wood asobserved by FTIR-ATR and UVRR spectroscopy. Holzforchung. 66(2):163–170. https://doi.org/10.1515/HF.2011.148

Goichman BD, Moshensky AD, Selezneva LV (1968) On the issue of assessing the shelf life of polymer materials on thermal ageing. Kauch Rezina 4:49–50

Goichman BD, Smukhunova T (1980) Prediction of changes in polymer materials properties during long-term storage and operation. Usp Khim 49(8):1554–1573

Gonzalez C, Meyers GE (1993) Thermal-degradation of wood fillers at the melt-processing temperatures of wood-plastic composites—effects on wood mechanical-properties and production of volatile. J Polym Mater 23:67–85. https://doi.org/10.1080/00914039308009660

Griciute G, Bludzius R, Norvaisiena R (2013) The durability test method for external thermal insulation composite system (ETICS) used in cold and wet climate countries. J Sustain Arch Civ Eng 1:50–56. https://doi.org/10.5755/j01.sace.1.2.2778

Idirs UD, Aigbodion VS, Gadzama RM, Abdullahi J (2011) Eco-Friendly (Watermelon Peels) alternatives to wood-based particleboard composites. Pacific J Sci Technol 12(2):112–119

Kadimaliev D, Telyatnik V, Revin V, Parshin A, Allahverdi S, Gunduz G, Kezina E, Asik N (2012) Optimization of the conditions required for chemical and biological modification of the yeast waste from beer manufacturing to produce adhesive compositions. BioResour 7(2):1984–1993. https://doi.org/10.15376/biores.7.2.1984-1993

Kadimaliev D, Kezina E, Telyatnik V, Revin V, Parchaykina O, Syusin I (2015) Residual brewer's yeast biomass and bacterial cellulose as an alternative to toxic phenol-formaldehyde binders in production of pressed materials from waste wood. BioResour 10(1):1644–1656. https://doi.org/10.15376/biores.10.1.1644-1656

Kadimaliev DA, Revin VV, Shutova VV (2001) Influence of pressing on lignin properties of pine wood treated with *Panus tigrinus* fungus. Khimija rastitel'nogo syr'ja 3:111–118

Kadimaliev DA, Revin VV, Shutova VV, Samuilov VD (2004) Use of the fungus *Panus tigrinus*in the manufacture of pressed materials from cotton plant waste. Appl Biochem Microbiol 40(1):49–52. https://doi.org/10.1023/B:ABIM.0000010351.03034.0a

Khrulev VM, Martynov KJ (1977) Durability of particle boards. Lesnaya promyshlennost', Moscow

Khrulev VM, Mashkin NA (1983) Assessment of the aging of modified wood by measuring swelling pressure. News of higher education institutions. Lesnoy Zhurnal 4:91–96

Kiselyova OA, Yartsev VP (2003) Dissertation topic: Prediction of efficiency of wood-particle and wood-fibre composites in construction products. Dissertation for the degree of candidate of technical science. Voronezh State University of Architecture and Civil Engineering, Voronezh. Russian Federation, pp 208

Koči V, Madera J, Robert C (2012) Exterior thermal insulation sestems for FFC building envelopes: Computational analysis aimed at increasing service life. Energy Build 47:84–90

Li K, Geng X (2005) Formaldehyde-free wood adhesives from decayed wood. Macromol Rapid Commun 26(7):529–532. https://doi.org/10.1002/marc.200400594

Manin VN, Gromov AN (1980) Physical and chemical resistance of polymer materials in operation conditions, Chemistry, Moscow

Martynov KJ, Khrulev VM (1984) Study of accelerated aging of particle boards by mathematical planning of the experiment. News High Educ Inst: Constr 2:78–81

Masters LW, Brandt E (1989) Systematic methodology for service life prediction of building materials and components. Mater Struct 22:385–392. https://doi.org/10.1007/BF02472509

Novokuptsev NV, Revin VV (2017) Dissertation topic: Optimization of the cultivation conditions of Azotobacter vinelandii D-08 to increase the synthesis of levane used as a biological binder for obtaining biocomposition materials. Dissertation for the degree of candidate of biological sciences. Institute of Biochemistry and Physiology of Plants and Microorganisms, Saratov Russian Federation, pp 141

Pavlo B, Niemz P (2003) Effect of temperature on color and strength of spruse wood. Holzforschung 57(5):539–546. https://doi.org/10.1515/HF.2003.080

Pavlov NN (1982) Aging of plastics in natural and artificial conditions, Chemistry, Moscow

Revin V, Novokuptsev N, Kadimaliev D (2016a) Preparation of biocomposites using sawdust and lignosulfonate with a culture liquid of levan producer *Azotobacter vinelandii* as a bonding agent. BioRes 11(2):3244–3258. https://doi.org/10.15376/biores.11.2.3244-3258

Revin VV, Novokuptsev NV, Red'kin NA (2016b) Optimization of cultivation conditions for *Azotobacter vinelandii*D-08, producer of the polysaccharide levan,for obtaining biocomposite materials. BioResour 11(4):9661–9675. https://doi.org/10.15376/biores.11.4.9661-9675

Varankina GS, Chubinsky AN (2011) Reducing toxicity of wood board materials. Lesprominform 1:134–139

Vidrina TS, Artyomov AV, Dedyukhin VG, Buryndin VG (2007) Thermal aging of products based on wood composite materials. Khimija rastitel'nogo syr'ja 2:101–106

Zhang Y, Jiyou G, Haiyan T, Mingwei D (2011) Straw based particleboard bonded with composite adhesives. BioResour 6(1):464–476. https://doi.org/10.15376/biores.6.1.464-476