

Residual Brewer's Yeast Biomass and Bacterial Cellulose as an Alternative to Toxic Phenol-Formaldehyde Binders in Production of Pressed Materials from Waste Wood

Davud Kadimaliev,* Elena Kezina,* Vladimir Telyatnik, Victor Revin, Olga Parchaykina, and Ilya Syusin

Pressed composites can be produced from wood sawdust waste using modified yeast biomass, waste as a bio-adhesive, ultra-dispersed bacterial cellulose (UBC) as a binder, and preliminary chemical cross-linking. The materials obtained were not inferior to traditional materials based on the required levels of toxic phenol-formaldehyde resin and physical and mechanical parameters. Physical and mechanical properties of the materials depended on the amount and viscosity of the binder, as well as on the chemical structure and conditions of chemical cross-linking and modified UBC application. The strengths of the best examples of the materials obtained were approximately 17 to 20 MPa, the densities were in the range of 1207 to 1255 kg/m³, and the water absorption was less than 20%. During hot pressing, notable changes were observed in the wood particles at FTIR-ATR spectra frequencies of 3620 cm⁻¹, 3600 to 3000 cm⁻¹, 2920 cm⁻¹, 2850 cm⁻¹, 1770 cm⁻¹, 1650 cm⁻¹, 1560 cm⁻¹, and 1089 cm⁻¹. This is mainly due to the chemical and structural changes in lignin, hemicellulose, and binder.

Keywords: Yeast biomass; Bacterial cellulose; Adhesion; Pressed materials from wood waste

Contact information: Russian Federation, Saransk, NP Ogarev Mordovia State University, Faculty of Biotechnology and Biology, Department of Biotechnology, Bioengineering and Biochemistry, 430019;

* *Corresponding authors:* cadimded@yandex.ru; alenakezina@yandex.ru

INTRODUCTION

Woodchip boards (WCB) are traditionally widely used in the construction and furniture industries. Due to its high static bending strength parameters, the material is successfully used in construction as a substitute for plywood. Moreover, WCB production does not require the use of high-quality wood and can be based on the processing of lumber waste and other woodworking industry wastes. However, these materials are obtained using phenol-formaldehyde resins, which, while in service, emit phenol, formaldehyde, and many other toxic agents into the air. Concentrations of formaldehyde in living quarters equipped with furniture and building structures containing WCB may exceed occupational exposure limits by 5 to 10 times. This is a major constraint to the growth of WCB application in construction. Therefore, the toxicity reduction of woodchip boards is highly relevant (Carll 1986; Li and Geng 2005; Carlborn and Matuana 2006).

There are several basic ways to reduce WCB toxicity. Some examples include applying an insulating layer of facing and varnish-and-paint materials on the board surface, binder modification, development of rational modes of plate pressing, treatment

of the finished boards or woodchips with substances capable of forming stable compounds with formaldehyde, and preliminary biological modification of wood waste using microorganisms and enzymes followed by pressing (Kadimaliev *et al.* 2001; Kadimaliev *et al.* 2004; Idirs *et al.* 2011; Varankina and Chubinskiy 2011; Zhang *et al.* 2011).

One of the most promising ways to solve the boards' toxicity problem is the replacement of synthetic resins with environmentally friendly, cheap bio-binders, *i.e.*, adhesive compositions of natural origin. However, the high cost and low moisture resistance of these adhesives and the lack of application technology hinder their wide introduction into production of pressed materials. Meanwhile, some literature data indicates that compositions prepared from modified bioorganic waste can be used as substitutes of natural adhesives. For example, the authors have shown that the yeast residues with appropriate modification acquire adhesive properties and can be used as bio-adhesives for bonding paper, fabrics, and wood (Zhang *et al.* 2011; Kadimaliev *et al.* 2012).

Analysis of the literature and physico-mechanical tests suggest that bio-adhesives can be used as a binder (adhesive) for pressed materials production. However, it is necessary to choose conditions for the preparation and treatment of raw material (sawdust) with a bio-adhesive for press-mass fabrication and pressing modes, *i.e.*, temperature, pressure, and duration (Lambuth *et al.* 2003; Zhang *et al.* 2011). The goal of this study was to investigate the possibility of using bio-adhesives based on modified residual yeast and bacterial cellulose as a bio-binder in the manufacture of pressed materials from waste wood.

EXPERIMENTAL

Materials

Bio-adhesive was produced according to the procedure described in the articles of Kadimaliev *et al.* (2012a,b). Yeast waste (*Saccharomyces cerevisiae* var. *carlsbergensis*) from the beer manufacturing process was the object of the current investigation. Yeast used to manufacture beer was centrifuged at 3000 rpm for 10 min to precipitate the cells. The resulting yeast pellets, which had a relative moisture content of 74%, were treated with sodium hydroxide solutions with concentrations of 1, 3, 5, and 7% and with hydrochloric acid solutions with concentrations of 2, 4, 6, and 8% for 15 min and 30 min, respectively. The yeast and corresponding solutions of sodium hydroxide and hydrochloric acid were mixed with a 1:1 mass ratio. After treatment, the yeast solutions were centrifuged at 6000 rpm for 15 min. The resulting chemically modified yeast waste was used to prepare various compositions of glue products. Glycerin composed of 4 wt% modified yeast waste and 0.3 wt% modified yeast waste boric acid were added as plasticizing and antiseptic agents to prepare the glues. The total quantity and the number of living and whole cells were determined using the cell viability analyzer Vi-cell (Beckman) and light spectroscopy. The moisture content of the yeast was determined with a thermohydraulic moisture analyzer (A.N.D. MS-70, Japan) according to the Russian State Standard 14043-78, and the amount of the amino groups were estimated by titration (Rafikov 1978). The viscosity of the glue was estimated using a Gotech Rion VT-04R viscometer (Gotech Testing Machines, China). To obtain bacterial cellulose, the bacteria *Gluconoacetobacter sucrofermentans* were cultivated for 7 days at room

temperature in a lightproof vessel. To remove bacterial cells, the bacterial cellulose was washed 5 to 6 times with 1 N NaOH. After alkali treatment, the bacterial cellulose was washed with distilled water until a pH of 7 was attained. The bacterial cellulose was then air-dried at room temperature and ground to nano- and micro-scale sizes in a Fritsch Pulverisette 7 planetary ball micromill (Germany). The size of the cellulose particles was determined by laser diffraction analysis (Shimadzu SALD-3101, Shimadzu, Japan) before they were mixed with bio-adhesive (Choi *et al.* 2009). To analyze the samples, weighed portions of 25 to 50 mg of cellulose particles were re-suspended in 50 mL of distilled (deionized) water, mixed thoroughly, and poured into an ultrasonic cell analyser. After 4 to 5 min of ultrasonic treatment, the sample was fed into the device and circulated through the analytical cell until a stable reading could be taken. Additionally, Photocor Complex particle size analyzers were used (Photocor Instruments, Antek-97, Russia) to analyze the size of cellulose particles. This instrument is based on static and dynamic light scattering (photon correlation spectroscopy), and the technique is designed for measurements of nanoparticle size, diffusion coefficients, and molecular weight of polymers in solutions.

To prepare amino derivatives, the bacterial cellulose (UBC) was oxidized by potassium iodate with subsequent separation of the insoluble fraction. Modified bacterial cellulose was washed several times with acetone to form a dialdehyde cellulose (DAC) (Sjutkin *et al.* 1999). After drying and acetone removal, DAC was immersed into 2 M urea solution for 2 to 4 h in order to modify DAC into amino cellulose (Kuznetsova *et al.* 1967). The binder was produced by mixing the modified residual beer yeast (bio-adhesive) and modified bacterial cellulose (UBC) in the ratio 9:1. Pine sawdust with particle sizes of about 3 to 5 mm, was received from the WCB manufacturing plant. Press-mass was obtained by mixing a binder with sawdust in different ratios.

Bio-adhesive viscosity was determined using a Gotech VT-04F viscometer (Gotech Testing Machines Inc., China). Pine sawdust with particle sizes of about 3 to 5 mm was received from the WCB manufacturing plant. The moisture content of pine-sawdust and press-mass was determined with an MS-70 thermohydraulic moisture analyzer (A.N.D. MS-70, Japan).

The density of WCB was determined on an H-300S densitometer (Hildebrand Pruf und Messtechnik GmbH, Germany, State Standard 10634-88 (1991)). The water sorption and volume swelling of WCB was determined according to State Standard 10634-88 (1991). To improve the moisture resistance of the composite material samples, 25% glutaric dialdehyde (NevaReaktiv, Russia) solution and modified cellulose were additionally introduced to the press-mass.

Methods

For bioplastics manufacturing, pine sawdust was mixed with the bio-adhesive using ultra-dispersed cellulose as a binder. The binder viscosity was adjusted with water. To obtain press-mass, sawdust was mixed with a binder by the extrusion method. Sawdust (100 g) was mixed with 50, 70, or 90 mL of binder (bio-adhesive containing 10% w/v UBC) and dried in an oven at 60 °C to a moisture content of 6 to 8%.

To obtain the composite, all components were loaded into a mold (5 x 15 cm). The mixture was pressed at room temperature at a pressure of 0.5 MPa for 1 min and then was subjected to hot-pressing by a hydraulic press (Gotech GT-7014M-A50, China) at a temperature of 160 and 180 °C and pressure of 3 to 5 MPa per 1 mm of thickness. Pressing time was calculated as 30 s per each millimeter of plate thickness. The thickness

of WBC was 10 to 11 mm, so the total time spent pressing was 5 min. The bending strength was determined according to State Standard 10635-88 (1989).

The resulting composites were tested for physico-mechanical properties and compared to the State Standard 10632-89 (2007). The bending strength was determined according to State Standard 10635-88 (1989) using a Gotech AI-7000M universal testing machine (Taiwan). Density was measured with a Hildebrand H-300S automatic densitometer (Hildebrand Pruf und Messtechnik GmbH, Germany). Distribution of sawdust and binders in the boards was analyzed by multifunction scanning electron microscopy (SEM Qanta 3D 200i, FEI Company, USA-Holland). The SEM images were obtained at an accelerating voltage of 20 kV and in a low vacuum of 60 Pa. For detection of chemical and structural changes in the board composites, attenuated total reflection (ATR) spectra of samples were analyzed in the range of 4000 to 800 cm^{-1} using an IRPrestige-21 Fourier transform infrared (FTIR) spectrometer (Shimadzu Co., Japan) and attached ATR unit (ATR-8200H with ZnSe prism without accessory recording function) with a resolution of 4 cm^{-1} . Samples from different parts of the woodchip boards (sample length 5 cm, width 1 cm, thickness 1 cm) were pressed to the ATR-crystal. Control samples of the boards were prepared by cold pressing only under the same conditions.

RESULTS AND DISCUSSION

The main difficulty in WCB production is the presence of a large number of interrelated factors. These factors include the strength characteristics of materials, heat- and soundproof properties, and environmental, aesthetic, and economic indicators. These indicators are affected by temperature, time, compression pressure, and binder/sawdust ratio. The basic operational indicator of pressed materials is strength at static bending. In order to achieve the normative strength values, boards should be made under certain process conditions. In test samples, bio-adhesive was mixed with UBC. As can be seen from Fig. 1 (a, b) UBC sizes ranged from 320 nm to 100 micrometers (Fig. 1a), but at the UBC, particles were found at 100 nm (Fig. 1b).

Therefore, experiments were performed in boards formed at compression temperatures of 160 and 180 °C, at pressure 39.2 MPa (3 to 5 MPa per 1 mm thickness), and specific duration of pressing (30 sec/mm of board thickness). At the end of pressing, boards were cooled at a low pressure for 5 min.

Results showed that the use of bio-adhesive with UBC as a binder affects the physical and mechanical properties of samples. The extent of the influence depended on the binder amount (Tables 1 and 2). Data presented in Tables 1 and 2 show that the addition of a binder based on modified residual beer yeast increases the strength characteristics of the boards. Physico-mechanical properties of the boards supplemented with 70 mL and 90 mL of adhesive differed only slightly.

Samples possessing better properties were obtained from the press-mass with the addition of 70 and 90 mL of bio-adhesive with viscosity of 1 dPa containing 10% ultra-disperse cellulose. Ultra-dispersed microparticles probably held together with bio-adhesive and penetrated into the wood pores, giving additional strength. During mixing of the binder with sawdust, impregnation of wood particles occurred.

Through hot pressing of the press-mass, excess moisture evaporated and a solid structure was formed due to the reactions between free functional groups of the adhesive and wood (Figs. 2a and 2b).

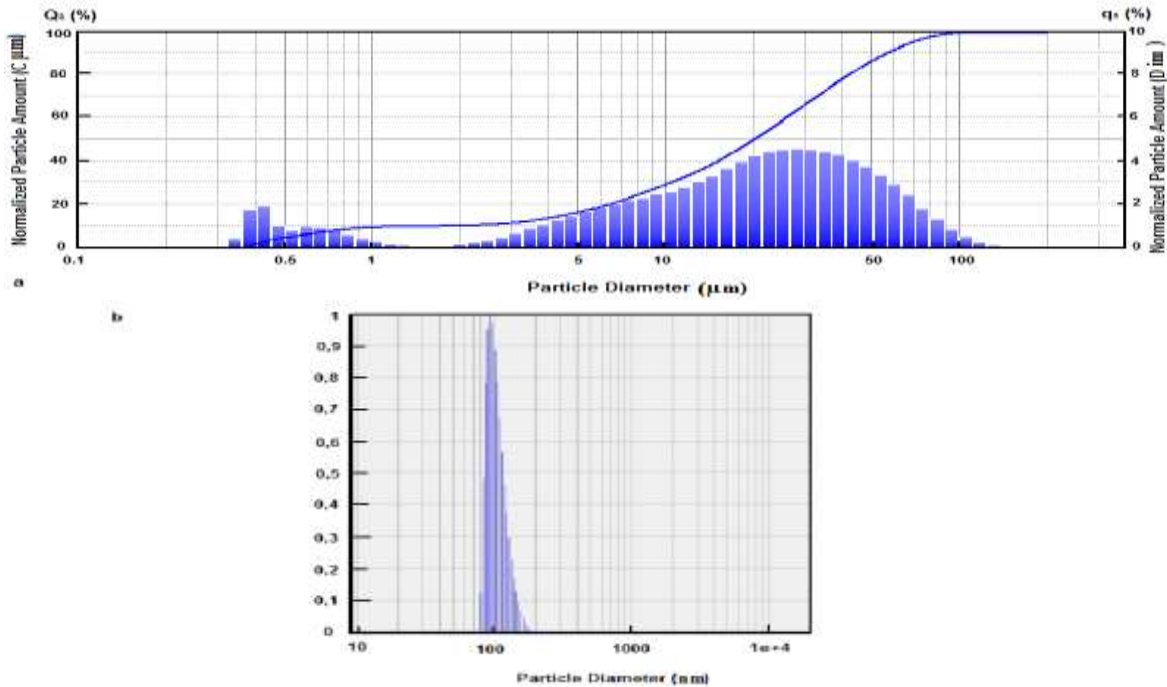


Fig. 1. Sizes of ultrafine bacterial cellulose particles after grinding: (a) UBC particle size distribution after grinding and (b) nanoparticle size distribution in UBC after grinding

Table 1. Physico-Mechanical Characteristics of the Boards Obtained at Pressing Temperature 160 °C (Average ± Standard Deviation)

Indicator	Pressed materials samples			
	The amount of binder (bio-adhesives) per 100 g of sawdust without / with 10% UBC (mL)			
	0	50	70	90
Tensile strength (MPa)	7.2±0.2/ 7.9±0.2	11.2±0.3/ 13.2±0.4	15.7±0.4/ 17.7±0.3	17.5±0.5/ 19.5±0.4
Density (kg/m ³)	1002.0±32.8/ 1092.0±31.6	1054.0±31.6/ 1154.0±32.6	1184.0±335/ 1189.0±35.5	1180.0±32.4/ 1189.0±35.4
Swelling in water by thickness (%)	Samples were destroyed	187.3±9.1/ 177.3±9.3	62.8±2.1/ 62.8±3.1	50.6±6.9/ 52.6±7.9
Water absorption (%)	Samples were destroyed	-	58.5±6.9/ 56.5±6.7	40.1±4.9/ 36.1±6.9

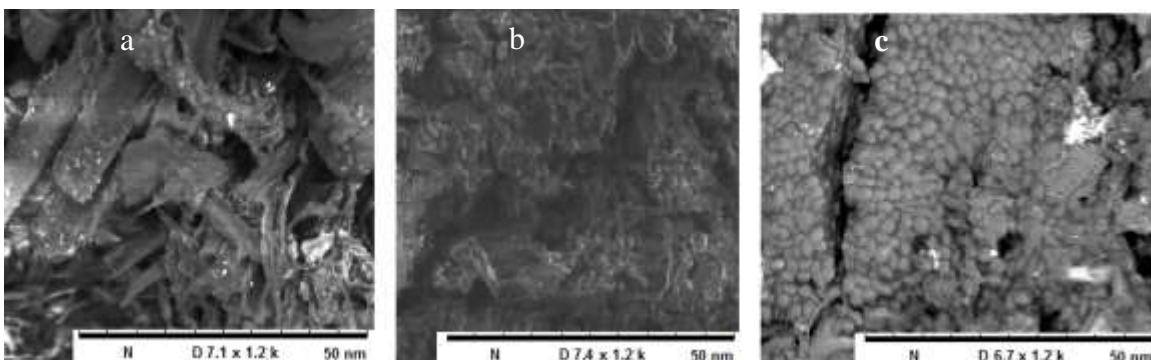


Fig. 2. SEM micrographs of woodchip boards: (a) boards without bio-binder, (b) boards with bio-binder of optimum viscosity, and (c) boards with high viscosity bio-binder

Table 2. Physical and Mechanical Properties of the Boards Obtained at Pressing Temperature of 180 °C (Average \pm Standard Deviation)

Indicator	Pressed Materials Samples			
	The amount of binder (bio-adhesives) per 100 g of sawdust without / with 10% UBC (mL)			
	0	50	70	90
Tensile strength (MPa)	8.1 \pm 0.2/ 8.7 \pm 0.2	14.6 \pm 0.3/ 15.6 \pm 0.4	16.9 \pm 0.3/ 18.9 \pm 0.4	17.7 \pm 0.4/ 19.7 \pm 0.5
Density (kg/m ³)	1248.0 \pm 32.2/ 1278.0 \pm 37.4	1217.0 \pm 31.5/ 1267.0 \pm 36.4	1231.0 \pm 34.9/ 1271.0 \pm 36.9	1255.0 \pm 40.6/ 1265.0 \pm 41.3
Swelling in water by thickness (%)	Samples were destroyed	149.5 \pm 7.3/ 140.6 \pm 7.1	50.8 \pm 2.7/ 54.6 \pm 2.9	30.8 \pm 1.2/ 35.8 \pm 1.7
Water absorption (%)	Samples were destroyed	135.9 \pm 6.1/ 130.9 \pm 6.7	47.2 \pm 2.1/ 40.2 \pm 2.3	31.5 \pm 1.3/ 27.5 \pm 1.5

Use of a bio-adhesive with a viscosity of more than 1 dPa reduced the quality of the boards. After pressing, the bio-adhesive appeared in the form of balls, and cracks were observed in the boards (Fig. 2c).

According to the State Standard 10635-88 (1989), chipboards with thicknesses of 10 to 11 mm should have a bending strength of 14 MPa. This is probably due to the fact that press-mass was less homogeneous and spread poorly. Zhang *et al.* (2011) and van den Bulcke *et al.* (2013) also showed that the heterogeneity of pressed boards and their poor quality is associated with viscosity and with the ratio of the main component to a binder.

Pressing at temperatures above 180 °C also was ineffective because the boards burned and became dark. Therefore, further experiments were carried out using 70 mL of binder and pressing at a temperature of 180 °C. However, despite the fact that many samples had high physical-mechanical characteristics, all resulting boards had low rates of water absorption and swelled in thickness. A control sample and samples with small amounts of bio-adhesive were destroyed after 2 h soaking in water (Tables 1 and 2).

As can be seen from the data presented, none of the obtained samples met the State Standard requirements in terms of swelling with water. This is probably due to the adhesive bonds' destruction in a hydrophilic binder during wood particle swelling in chipboard (a phenomenon called "decompression").

In a previous study, it was shown that the introduction of glutaric dialdehyde 5% solution into adhesive composition increases moisture resistance (Kadimaliev *et al.* 2012). This is due to the formation of proteins cross-linked by amino groups with strong azomethine (Fernandez-Lorente *et al.* 2006; House *et al.* 2007).

Therefore, to improve the pressed materials moisture resistance, different quantities of glutaric dialdehyde 5% solution were added to the press-mass. Furthermore, in order to increase the reactivity towards proteins and glutaraldehyde, ultra-dispersed cellulose was chemically modified by amino groups grafting prior to adding to the adhesive. Amino group formation was estimated by the changes in the FTIR spectra (Fig. 3) and visually (Fig. 4).

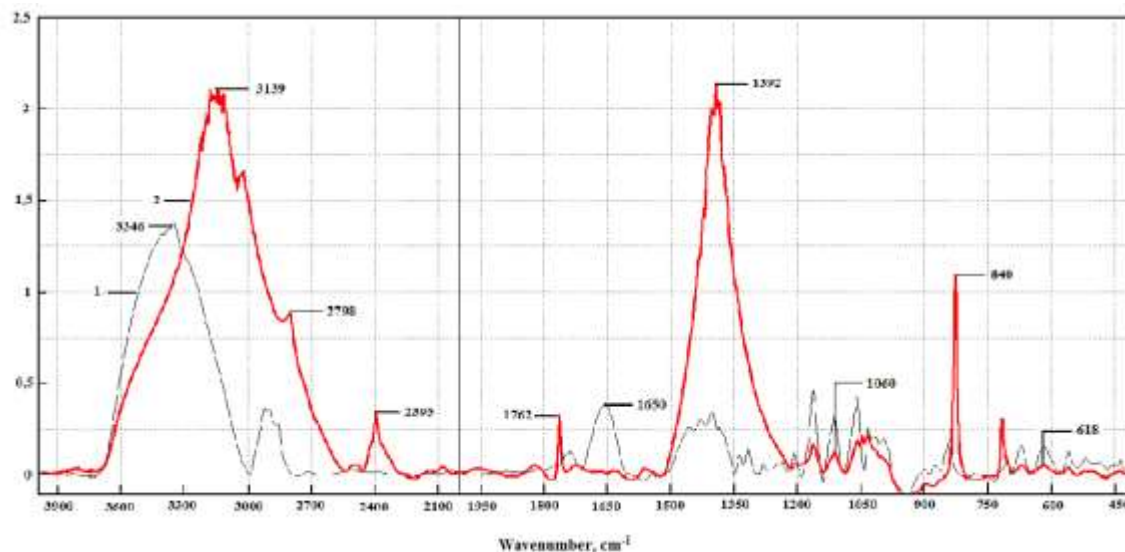


Fig. 3. FTIR spectrum of bacterial cellulose: 1-IR spectra of the native dried UBC and 2-IR spectra of the UBC amino derivative.

Boards with high binder content increased in weight and swelled in thickness due to water absorption, but they retained their structures. Thus, the binder amount affected both moisture resistance and material strength.

As shown in Fig. 3, the FTIR spectra of bacterial cellulose ultra-dispersed particles corresponded to spectra described in the literature (Ciolacu *et al.* 2011; Cook 2013). During modification, absorption intensity of bacterial cellulose in the IR spectra in the 3500 to 3200 cm^{-1} range caused by amino groups increased and decreased in the 3600 to 3000 cm^{-1} range, which indicates that during chemical modification a partial substitution of hydroxyl groups by amino groups occurred (Smith 1979; Pretsch *et al.* 2006; Vasiliev and Grynenko 2007).

At the same time, absorption intensity in the aromatic ring oscillation region at 1200 to 900 cm^{-1} and the background absorption at 800 to 400 cm^{-1} decreased due to pyranose ring vibrations and deformation vibrations of hydroxyl groups (Fengel and Wegener 2003). This can be explained by the fact that during the chemical modification of cellulose by oxidation with iodic acid or its salts, a simultaneous oxidation of both secondary hydroxyl groups to aldehyde groups (band at 840 cm^{-1}) occurred, accompanied by a break of the pyranose ring unit of the cellulose macromolecule.

The presence of amino groups in the modified cellulose can be confirmed by the fact that glutaric dialdehyde addition led to the formation of a brownish-red strong insoluble film due to azomethine linkage formation between aldehyde and amino groups. With the original cellulose, the film was viscous, sticky, and had no visible signs of the amino groups' presence. After drying, the mixture of sawdust with adhesive became reddish, indirectly confirming azomethine linkage formation between aldehyde and amino groups (Fig. 4). An intermediate product was formed in this process, *i.e.*, dialdehyde cellulose with an absorption band (crystallinity strip) with a maximum frequency of 1392 cm^{-1} , corresponding to scissor vibrations of the methylene group, C1 atom vibrations, and vibrations of four atoms in the p-glycosidic structures surrounding C1.

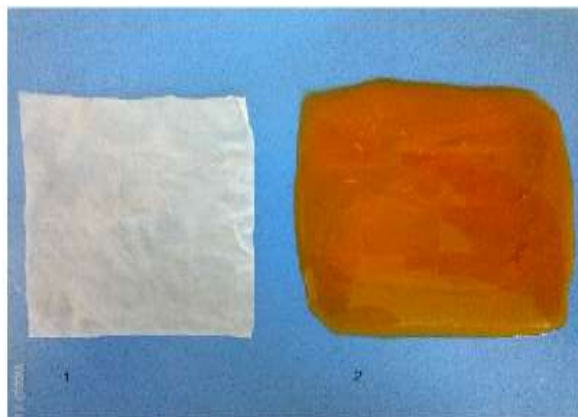


Fig. 4. Polymer mixtures based on UBC: (1) polymer composition based on non-modified UBC (control) and (2) polymer composition based on the amino-cellulose derived from UBC supplemented with glutaric dialdehyde (test sample)

The absorption at 1650 cm^{-1} spectra of unmodified cellulose was caused by adsorbed water (Bazarnova *et al.* 2002; Yin *et al.* 2009; Kristiansen *et al.* 2010; Tlupova *et al.* 2012).

From data in Tables 2 and 3, it is evident that the control sample and sample without cross-linking disintegrated after soaking in water. Samples with glutaric dialdehyde and modified cellulose addition swelled in thickness considerably and increased their weight due to moisture absorption but did not disintegrate. At the same time, the strength of the boards increased slightly (Thoemen *et al.* 2010). With the increase of the cross-linking amount up to 15 mL, the material moisture resistance increased.

Table 3. Physical and Mechanical Properties of the Boards Obtained with Addition of Glutaric Dialdehyde and Modified Cellulose (Average \pm Standard Deviation)

Indicator	Samples of pressed materials Amount of glutaric dialdehyde in the press-mass (mL)				
	0	5	10	15	20
Tensile strength (MPa)	8.1 \pm 0.2	18.8 \pm 0.5	20.9 \pm 0.7	17.8 \pm 0.7	15.8 \pm 0.7
Density (kg/m ³)	1255.0 \pm 40.6	1207.0 \pm 48.2	1224.0 \pm 46.5	1249.0 \pm 46.2	1224.0 \pm 46.5
Swelling in water by thickness (%)	35.8 \pm 1.7	25.3 \pm 1.2	21.1 \pm 1.1	20.2 \pm 1.2	18.2 \pm 1.2
Water absorption (%)	31.5 \pm 1.5	22.4 \pm 1.1	20.2 \pm 1.2	18.1 \pm 1.0	16.1 \pm 1.0

Addition of glutaric dialdehyde solution in amounts more than 15 mL into the press-mass reduced the strength characteristics of the boards. This is probably due to the fact that the excess cross-linking blocked fully functional amino groups as possible participants of adhesion.

In the literature, questions are widely discussed concerning the chemical and structural changes occurring during hot pressing in the press-mass components (wood particles and binders). According to some authors (Bazarnova *et al.* 1997a,b; Kadimaliev *et al.* 2001), mainly functional groups of lignin and hemicellulose contribute to bond

formation between the components. Cellulose changes only slightly and plays the role of a frame.

Other authors consider that functional groups of polysaccharides are also involved in the process of WCB component cross-linking (Sivonen *et al.* 2002; Hennecke and Roffael 2006; Muller *et al.* 2009). To investigate the changes in the organic compound structures of the wood components, many authors recommend Fourier transform infrared (FTIR) spectroscopy (Fengel and Wegener 2003; Muller *et al.* 2009). This method also allows analysis of the formation of bonds between wood particles, wood components, and binders (Fabo 2004).

Fourier transform infrared-ATR spectroscopy has been used in combination with scanning electron microscopy (Zhang *et al.* 2011). These studies have shown that FTIR-ATR spectra of WCB did not differ significantly from the typical IR spectra for wood components (Fig. 5). During hot pressing, changes occur in the absorption intensity of functional groups of the pressed materials components. As shown in Figure 5, at cold pressing the board samples had spectra typical for the wood components cellulose, lignin, and hemicellulose.

During hot pressing in the absence of a binder, changes were observed in the FTIR-ATR spectra of wood particles at frequencies 3620 cm^{-1} , $3600\text{ to }3000\text{ cm}^{-1}$, 2920 cm^{-1} , 2850 cm^{-1} , 2850 cm^{-1} , 1770 cm^{-1} , 1650 cm^{-1} , 1560 cm^{-1} , and 1089 cm^{-1} .

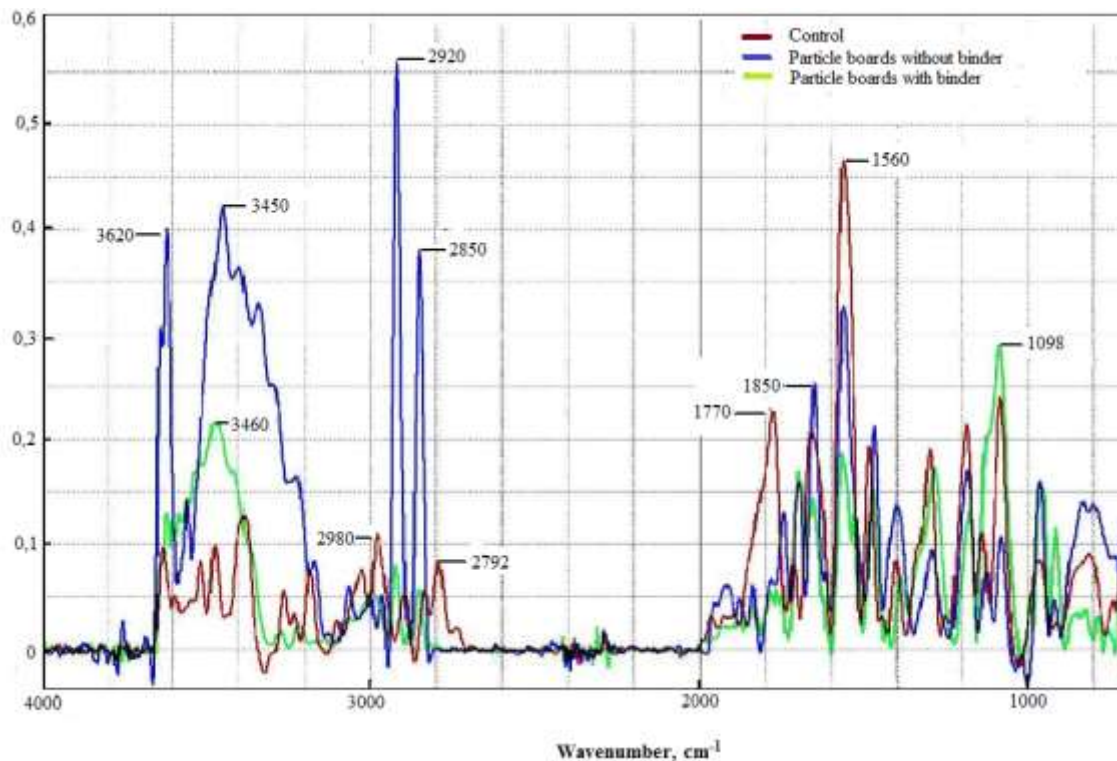


Fig. 5. FTIR-ATR mean spectra of boards obtained by cold pressing (control, red), experimental boards obtained by hot-pressing without adhesive (blue), and with adhesive (green)

According to the literature, the absorption at 3620 cm^{-1} is caused by stretching vibrations of OH-groups not connected by hydrogen bonds; at $3600\text{ to }3000\text{ cm}^{-1}$, the absorption is caused by stretching vibrations of OH-groups involved in hydrogen bonds in cellulose, lignin, and hemicellulose (Bazarnova *et al.* 2002; Fengel and Wegener 2003).

In the area of 2920 cm^{-1} to 2850 cm^{-1} , the absorption is caused by CH- stretching vibrations of methyl and methylene groups in lignin, and at 1770 cm^{-1} the absorption is caused by C=O vibrations in the ester group of hemicelluloses (Fengel and Wegener 1989; Bazarnova *et al.* 2002; Fengel and Wegener 2003) and uronic acids (Bazarnova *et al.* 2002; Muller *et al.* 2009). A peak at 1650 cm^{-1} is caused by adsorption of OH-groups and conjugated C-O bonds or carbonyl and carboxyl groups in the lignin (Pandey and Pitman 2003). A peak at 1560 cm^{-1} is caused by skeletal vibrations of the aromatic ring (Roeges and Noel 1995), and at 1089 cm^{-1} the peak is caused by stretching vibrations of C-O bonds characteristic for the primary, secondary, and tertiary hydroxyl groups in the lignin (Bazarnova *et al.* 2002).

During hot pressing, a softening of lignin and the partial destruction of β -O-4-bonds between the aromatic ring monomers occur; demethylation and oxidation reactions also proceed (Bazarnova *et al.* 1997b; Garrote *et al.* 2001; Sivonen *et al.* 2002). This results in an increase in the amount of OH-groups involved in hydrogen bonding (3000 to 3620 cm^{-1}), methyl and methylene groups (2920 cm^{-1} , 2850 cm^{-1}), and carbonyl and carboxyl groups (1650 cm^{-1}). The absorption decrease at 1770 cm^{-1} indicates a partial destruction of hemicellulose and at 1560 cm^{-1} , a partial destruction of the aromatic ring (Hennecke and Roffael 2006).

In boards produced by hot-pressing in the presence of a binder, a sharp decrease in absorption is observed at 3620 cm^{-1} , 3000 to 3600 cm^{-1} , 2920 cm^{-1} , 2850 cm^{-1} , and 1770 cm^{-1} , which may be due to the formation of new bonds between the binder and disintegration products of lignin and hemicellulose, *e.g.*, by polycondensation and polymerization reactions (Bazarnova *et al.* 1997 a, c; Muller *et al.* 2009).

CONCLUSIONS

1. Yeast biomass and ultra-dispersed bacterial cellulose, after appropriate modification, can be used as a bio-binder in the production of pressed materials from plant raw material waste.
2. Chemical modification of yeast biomass and bacterial cellulose led to formation of reactive groups, which improved the quality of the bio-adhesive.
3. The quality of pressed materials from waste wood depended on the conditions of pressing and properties of the bio-adhesive.

ACKNOWLEDGMENTS

The authors are grateful for the support of the Ministry of Education and Science of the Russian Federation, Grant. No. 2913 reg. 01 10 0210059 611. The authors are thankful to Dr. V.P. Mishkin and B.F. Mamin for help in the SEM studies.

REFERENCES CITED

Bazarnova, N. G., Galochkin, A. I., Glebov, and Yu, L. (1997a). "Pressed materials of hydrothermally treated wood and dicarboxylic acid anhydrides," *Chemistry of Plant Raw Material* 2 (1), 15-22.

- Bazarnova, N. G., Galochkin, A. I., and Krestyannikov, V. S. (1997b). "Effect of wood hydrothermal treatment on properties of wood pressed materials," *Chemistry of Plant Raw Material* 2(1), 11-16.
- Bazarnova, N. G., Galochkin, A. I., and Krestyannikov, V. S. (1997c). "Urea influence on the properties of pressed materials made of wood subjected to a hydrothermal treatment," *Chemistry of Plant Raw Material* 2(1), 22-30.
- Bazarnova, N. G., Karpova, E. V., Katrakov, I. B., Markin, V. I., Mikushina, I. V., Olkhov, Yu. A., and Khudenko, S.V. (2002). *Methods of Investigation of Wood and Its Derivatives*, Altai University Publisher, Barnaul, p. 160.
- van den Bulcke, J., Biziks, V., Andeersons, B., Mahnert, K.-C., Militz, H., Loo, D., Dierick, M., Masschaele, B., Boone, M. N., Brabant, L., De Witte, Y., Vlassenbroeck, J., van Hoorebeke, L., and Van Acker, J. (2013). "Potential of X-ray computed tomography for 3D anatomical analysis and microdensitometrical assessment in wood research with focus on wood modification," *International Wood Products Journal* 4(3), 183-190. DOI: 10.1179/2042645313Y.0000000046.
- Carll, C. (1986). "Wood particleboard and flakeboard: Types, grades, and uses," *General Technical Report FPL-GTR-53*, U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI. p. 9.
- Carlborn, K. L. M., and Matuana L. M. (2006). "Influence of processing conditions and material compositions on the performance of formaldehyde-free wood-based composites," *Polymer Composites* 27, 599-607. DOI: 10.1002/pc.20175.
- Choi, H., Lee, W., Kim, S. (2009). "Optimum refractive index of poly-component particulate systems for measurement of particle size distribution by laser diffraction method analyzer," *Materials Chemistry and Physics*. 117(1), 18-22. DOI: 10.1016/j.matchemphys.2009.05.035
- Ciolacu, D., Ciolacu, F., Popa, V. I., Poni, P., and Asachi, G. (2011). "Amorphous cellulose-structure and characterization," *Cellulose Chemistry and Technology* 45 (1-2), 13-21.
- Cook, J. R. (2013). *Amine Functionalization of Bacterial Cellulose for Targeted Delivery Applications*, Master's Thesis, University of Western Ontario, Canada, pg. 256.
- Fabo, A. (2004). *Untersuchungen zur Wechselwirkung von Polyethylenimin (PEI) mit Holzkomponenten*, Dissertation, Universität Hamburg, Hamburg, Germany, pg.160.
- Fengel, D., and Wegener, G. (1989). "Wood - Chemistry, Ultrastructure, Reactions," *Rtssel Verlag, Remagtn.*, pg. 270.
- Fengel, D., and Wegener, G. (2003). "Wood: Chemistry, Ultrastructure, Reactions," *Rtssel Verlag, Remagtn.*, pg. 613.
- Fernandez-Lorente, G., Palomo J. M., Mateo, C., Munilla, R., Ortiz, C., Cabrera, Z., Guisan, J. M., and Fernandez-Lafuente, R. (2006). "Glutaraldehyde cross-linking of lipases adsorbed on aminated supports in the presence of detergents leads to improved performance," *Biomacromolecules* 7(9), 2610-2615. DOI: 10.1021/bm060408.
- Garrote, G., Dominguez, H., and Parajo, J. C. (2001). "Study on the deacetylation of hemicellulose during the hydrothermal processing of *Eucalyptus* wood," *Holz als Roh- und Werkstoff* 59(1-2), 53-59. DOI: 10.1007/s001070050473.
- Hennecke, U., and Roffael, E. (2006). "Veränderungen der chemischen Eigenschaften von Fasern und MDF durch Waschern der aufgeschlossenen Fasern," *Holz als Rohund Werkstoff* 64(4), 305-311. DOI: 10.1007/s00107-005-0079-3.

- House, J. L., Anderson, E. M., and Ward, W. K. (2007). "Immobilization techniques to avoid enzyme loss from oxidase-based biosensors: A one-year study," *Journal of Diabetes Science and Technology* 1(1), 18-27.
- Idirs, U. D., Aigbodion, V. S., Gadzama, R. M., and Abdullahi, J. (2011). "Eco-friendly (watermelon peels) alternatives to wood-based particleboard composites," *The Pacific Journal of Science and Technology* 12(2), 112-119.
- Kadimaliev, D. A., Revin, V. V., and Shutova, V. V. (2001). "Effect of pressing on the properties of lignin of pine wood treated with *Panus Tigrinus*," *Chemistry of Plant Raw Materials* 3, 111-118.
- Kadimaliev, D., Telyatnik, V., Revin, V., Parshin, A., Allahverdi, S., Gunduz, G., Kezina, E., and Asik, N. (2012a). "Optimization of the conditions required for chemical and biological modification of the yeast waste from beer manufacturing to produce adhesive compositions," *BioResources* 7(2), 1984-1993.
- Kadimaliev, D. A., Revin, V. V., Shutova, V. V., and Samuilov, V. D. (2004). "Use of the Fungus *Panus tigrinus* in the manufacture of pressed materials from cotton plant waste," *Applied Biochemistry and Microbiology* 40, 49-52.
DOI:10.1023/B:ABIM.0000010351.03034.0a.
- Kadimaliev, D. A., Telyatnik, V. I., Kadimaliev, E. D., and Parshin, A. A. (2012b). "Glue composition," *RU Patent 2457232*.
- Kristiansen, K. A., Christiansen, B. E., and Potthast A. (2010). "Periodate oxidation of polysaccharides for modification of chemical and physical properties," *Carbohydrate Research* 345 (10), 1264-1271. DOI: 10.1016/j.carres.2010.02.011.
- Kuznetsova, N. Y., Timokhina, G. A., and Ivanov, V. M. (1967). "A method for producing amine derivatives of cellulose," *SU Patent 203665*.
- Lambuth, A. L., Pizzi, A., Mittal, K. L., and Dekker, M. (2003). "Protein adhesives for wood," *Handbook of Adhesive Technology* 20, 1-12.
- Li, K., and Geng, X. (2005). "Formaldehyde-free wood adhesives from decayed wood," *Macromolecular Rapid Communications* 26(7), 529-532.
DOI:10.1002/marc.200400594.
- Muller, G., Schopper, C., Vos, H., Kharazipour, A., and Polle, A. (2009). "FTIR-ATR spectroscopic analyses of changes in wood properties during particle- and fibreboard production of hard- and softwood trees," *BioResources* 4(1), 49-71.
- Pandey, K. K., and Pitman, A. J. (2003). "FTIR-ATR studies of the changes in wood chemistry following decay by brown-rot and white-rot fungi," *Intern. Biodetrior. Biodegr.* 52(3), 151-160. DOI: 10.1016/S0964-8305(03)00052-0.
- Pretsch, E., Bühlmann, F., and Affolter, K. (2006). "Tables of spectral data," in: *Determining the Structure of Organic Compounds*, E. Pretsch; P. Bühlmann; C. Affolter (eds.), Springer-Verlag Berlin Heidelberg New York, pp. 5-7.
- Raficov, S. R. (1978). *Introduction to Physics-Chemistry of Polymer Solutions*, S. R. Raficov (ed.), Publishing House Science, pg. 378.
- Roeges, and Noel P. G. (1995). "A guide to the complete interpretation of infrared spectra of organic structures," *J. Chem. Educ.* 72 (4), 77-81. DOI: 10.1021/ed072pA93.4.
- Sivonen, H., Maunu, S. L., Sundholm, F., Jamsa, S., and Viitamniemi, P. (2002). "Magnetic resonance studies of thermally modified wood," *Holzforschung* 56, 648-654. DOI: 10.1515/HF.2002.098.
- Sjutkin, V. N., Nikolaev, A. G., Sazhin, S. A., Popov, V. M., and Zamoryansky, A. A. (1999). "Nitrogen-containing derivatives of dialdehyde cellulose. Dialdehyde cellulose with high degree of oxidation," *Chemistry of Plant Raw Material* 2, 91-102.

- Smith, A. L. (1979). *Applied Infrared Spectroscopy: Fundamentals, Techniques, Analytical Application*, A.L. Smith (ed.), Wiley, New York, p. 318.
- State Standard 10632-89. (2007). "Woodchip boards. Technical specifications," Vved. 01.01.2009. – M.: Publishing standards, pg. 18.
- State Standard 10635-88. (1989). "Woodchip boards. Methods for determining the tensile strength and flexural modulus," Vved. 01.01.1990. – M.: Publishing standards, pg. 10.
- State Standard 10637-88. (1991). "Woodchip boards. The method of determining the physical properties," Vved. 01.01.1990. – M.: Publishing standards, pg. 195.
- State Standard 14043-78. (1999). "Polyvinylchloride and copolymers of polyvinylchloride. Method of determining the moisture and volatile component content," Vved.01.01.1979.M.: Publishing standards, pg.4.
- Thoemen, H., Irlle, M., and Sernek, M. (2010). *Wood-Based Panels - An Introduction for Specialists*, Brunel University Press, p. 287.
- Tlupova, Z. A., Zhansitov, A. A., Elcheparova, S. A., and Hashirova, S. Y. (2012). "New water soluble bactericidal materials based on dialdehyde cellulose and derivatives of diallyl guanidine," *Fundamental Research. Chemical Sciences* 11, 970-974.
- Varankina, G. S., and Chubinskiy, A. N. (2011). "Reducing the toxicity of wood boards materials," *Les Prom Inform* 1(75), 134-139.
- Vasiliev, A. V., and Grynenko, E. V. (2007). "Special aspects of infrared spectra of organic and natural products," in: *Infrared Spectra of Organic and Natural Products*, A. V. Vasiliev (ed.), St. Petersburg State Forest Engineering Academy, pp. 11-18.
- Zhang, Y., Gu, J., Tan, H., Di, M., Zhu, L., and Weng, X. (2011). "Straw based particleboard bonded with composite adhesives," *BioResources* 6(1), 464-476.
- Yin, X., Koschella, A., and Heinze, T. (2009). "Regioselectively oxidized 3-O-alkyl ethers of cellulose: Synthesis and characterization," *Reactive and Functional Polymers* 69(6), 341-346. DOI: 10.1016/j.reactfunctpolym.2009.02.010

Article submitted: October 10, 2014; Peer review completed: December 20, 2014;
Revised version received and accepted: January 14, 2015; Published: January 26, 2015.