Physical and mechanical characteristics of the thermal-wood composition from hydrolyzed birch wood

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Abstract. The article presents data on the influence of the conditions of barothermal processing of downly birch (Betula pubescens) wood and its hot pressing on the physico-mechanical properties of the resulting thermo-wood composition. Steam treatment is performed at a temperature of 200° C, the duration of the exposure time in the reactor is from 5 to 600 seconds. Dried samples of hydrolyzed wood were subjected to hot pressing at a temperature of 120 or 140 ° C under pressure of 4.0 and 5.3 MPa. It has been established that an increase in the hardness factor of hydrolysis is accompanied by an increase in the density of the obtained samples of the thermo-wood composition. The dependence of the strength characteristics on the rigidity of the conditions of barothermal treatment is complex, determined by the presence of a point of extremum, after which the strength characteristics begin to decrease. Based on the obtained results, the optimal conditions for obtaining the thermo-wood composition were determined. It is shown that barothermal treatment of birch wood with the purpose to obtain on its basis a thermowood composition with optimal physicomechanical characteristics is expedient under the conditions of a process stiffness factor of 2000 ... 2500 minutes.

1. Introduction

In the forests of Siberia there are many hardwood trees, one of which is birch [1]. Traditionally, birch wood is widely used in plywood, pulp-paper production, as well as in the manufacture of furniture. But the potential of this resource is still significant. The relatively low physical and mechanical properties of birch wood, its susceptibility to rotting at high moisture content do not allow the use of this species more widely. At present, methods for improving the protection of native wood from moisture penetration include the application of protective coatings – as paint or varnish, film and combined [2, 3]. These methods prevent the penetration of water into the interfiber space, but their use is associated with large labor costs and the expenditure of material resources. In addition, these methods do not lead to the improvement of other characteristics of the material, for example, does not increase its strength characteristics.

The aim of this work is to study the peculiarities of exposure of overheated steam to the native birch wood in the process of explosive auto hydrolysis and followed by hot pressing into a composite material. It was expected that the resulting thermowood composition should have improved physicomechanical characteristics and increased moisture resistance compared to the original wood. During the experiment, the conditions of barothermal processing and hot pressing were varied. This made
possible to affect the basic physicomechanical characteristics of the material and obtain the finished product with specified properties in a wide range.

2. Material and Methods
During the work, samples of solid downly birch wood (Betula pubescens) were used. The wood after cutting was aged for one year in a ventilated and unheated room. Birch of this species is one of the main species forming tree stands in deciduous and mixed forests of the Altai Territory. Sampling was made from the core of the trunk in the form of plates of a mixed (semi-radial) cut with a predominance of the tangential component. The size of the original plates was 150 × 50 × (~) 7 mm with a long side taken along the fibers.

Wood samples of air-dry degree of humidity (20...30%) were subjected to barothermal action of superheated saturated steam by the method of explosive autohydrolysis in a batch reactor [4, 5]. The processing temperature of all series of samples was 200 °C. The processing time varies from 5 seconds to 10 minutes. Thus, the severity factor of the process of explosive autohydrolysis, determined in accordance with the dependence [6-8]:

\[ R_0 = r_0 e^{(T-100)/14.75}, \]

where, T is the process temperature (°C), τ – is the process duration (min.), ranged from 73 to 8800 min.

After barothermal treatment, the obtained samples of hydrolyzed wood were dried in the conditions of a heated room to an air-dry degree of moisture (7...18%), determined by the state of stabilization of the mass.

Dried samples of hydrolyzed birch wood were placed in a collapsible mold for subsequent hot pressing at a temperature of 120 or 140 °C. The compaction pressure was 4.0 at 120 °C and 5.3 MPa 140 °C.

2.1. Description of the method of heating and pressing
The sample was placed in the press-form. Then the heating of the mold was turned on and the required pressure was set simultaneously. With a continuous increase in temperature, the pressure was maintained at the target value. After reaching a temperature which was lower than the target one by 5..7 °C, the heating was turned off, while the sample temperature continued to increase due to the inertia of the system. After a few minutes, the target value was achieved with an accuracy of ± 1.5 °C. Then, the sample was held at a given pressure and temperature for 3 minutes. After the expiration of the specified time, the pressure was removed and the press-form with the sample was gradually cooled to a temperature of 30 °C. Polycondensation processes occurring during hot pressing of hydrolyzed wood lead to compaction of the material due to formation of cross-linked intermolecular structures [9, 10]. The physico-mechanical properties of wood after barothermal treatment and hot pressing are significantly different from those of the original wood.

3. Results and Discussion
The authors investigated the samples of hydrolyzed wood that was not subjected to hot pressing and the samples after hot pressing. Control samples of the original wood were also examined. For all samples, the density value was determined. For several samples, the values of flexural strength and water absorption for 24 hours were determined. Studies were conducted by standard methods.

The dependence of the density of birch wood samples on the rigidity factor of the explosive autohydrolysis process is presented in Figure 1. The dependence is shown for birch wood samples subjected to barotherm treatment and not subjected to subsequent hot pressing into a composite material. There is a tendency to reduce the density of wood with an increase in the rigidity of the process of its barothermal treatment. Dependence is decreasing according to non-linear law.

We will assume that the significant variation in values is random and is due to the structural heterogeneity of the woody fabric of the processed samples. Structural heterogeneity may be due to the presence of internal defects, compaction zones, etc.
The results of the study may indicate that barothermal treatment of birch wood under conditions of process hardness \( R_0 = 73...4400 \) min. does not lead to significant destructive changes in the morphological structure. The consequence of processing in these conditions is the reduction in density of woody tissue by no more than 15 percent. Processing in more severe conditions, at \( R_0 = 8800 \) minutes, leads to a much more significant destruction. Such destruction may be accompanied by intensification of the fiber stratification process and a sharp decrease in the density of hydrolyzed woody tissue.

Hot pressing of hydrolyzed wood is accompanied by its considerable compaction caused by softening of the components of woody fabric. Compaction can also be the result of a polycondensation process with the formation of strong intermolecular bonds [9]. Figure 2 (a, b) shows a trend of uneven increase in the density of samples of composite material with an increase in the rigidity factor of barothermal treatment. From the presented pictures it is visible, that pressing at 140 °C with increase of \( R_0 \) leads to fast increase of density of a material. A sharp increase in density is observed already at small values of \( R_0 \). On contrary, under pressing conditions at a temperature of 120 °C of wood samples hydrolyzed at \( R_0 < 880 \) minutes, there is practically no increase in density.

As the value of \( R_0 \) increases, the density of the thermowood composite material obtained both at a pressing temperature of 120 °C and at a temperature of 140 °C is characterized by a conditional “saturation” area, when an increase in the rigidity of the barothermal treatment conditions does not...
lead to any further noticeable increase in the material density. As for the temperature of 120 °C and for the temperature of 140 °C, the aged "saturation" occurs at almost at the same values of \( R_0 \) (close to 3000 minutes). Such behavior of the material can be explained by the fact that the barothermal treatment up to \( R_0 = 3000 \) min. gradually increases the number of active groups involved in polycondensation processes during hot pressing. The morphological structure of wood tissue is slightly destroyed, as it evidenced by the relatively small change in the density of such samples directly after barothermal treatment (Figure 1). Therefore, in conditions of \( R_0 < 3000 \) min. crosslinking processes dominate over destruction processes. A further increase in the rigidity of the process contributes to the intensification of the processes of lignin destruction, accompanied by a significant degradation of wood fabric with the destruction of cellulose fibers. From this point, destructive processes begin to dominate over the processes of polycondensation. This can be confirmed by the nature of the dependence of the strength characteristics of the material on \( R_0 \) (Figure 3). As for the material obtained by extrusion at a temperature of 120 °C and for the material obtained at 140 °C, an increase in strength with an increase in the rigidity of the barothermal conditions is characteristic. The increase in strength continues only to the value of \( R_0 = 2000...2500 \) min. Then, with a further increase in \( R_0 \), there is a sharp deterioration in the strength of the material. It is characteristic that the value of the stiffness factor, after which the strength begins to decrease, correlates with the "saturation" point noted above in the plots of the dependences of density on \( R_0 \). Most likely, the value of the stiffness factor \( R_0 = 2000...2500 \) min determines an arbitral boundary, after reaching which the destruction of the structure of wood tissue begins to dominate over the formation of reactive groups. In practice, this means that barothermal treatment of birch wood to obtain a thermo-wood composition on its basis is impractical under conditions of process hardness exceeding this value.

**Figure 3.** Dependence of bending strength of a thermowood composition on the stiffness factor of barothermal treatment, pressed (a) at 120 °C, (b) at 140 °C.

Hot pressing of hydrolyzed wood both at a temperature of 120 °C and at 140 °C provides a similar result. In both cases in the "saturation" area, the density is about 1250 kg/m³. The strength is also approximately the same (200...220 MPa). Thus, it can be assumed that most of the reactive components participate in the polycondensation processes already at 120 °C. A higher pressing temperature (140 °C) contributes to somewhat better structural homogeneity of the materials obtained and more accurate reproducibility of the results.

The final stage was the analysis of the hydrophobic characteristics of the material. Figure 4 presents the water absorption values of the thermowood composition. There is a reverse exponential dependence of water absorption on \( R_0 \).
With an increase in $R_0$ to 2000...2500 min., a sharp decrease in water absorption is observed synchronously with the improvement of the strength characteristics. Increasing in the $R_0$ value over 2500 min. is accompanied by a weak decrease in water absorption. Obviously, the amount of water absorption is determined primarily by the presence of voids in the material structure. Their quantity and volume is density determined. The consequence is the almost linear character of the dependence of water absorption on density, shown in Figure 5.

Thus, a number of conditions of barothermal treatment of birch wood by the method of explosive autohydrolysis followed by hot pressing provide a thermowood composite material with improved characteristics in comparison with the characteristics of the original wood.

**Figure 4.** Dependence of water absorption for 24 hours of a thermowood composition on the hardness factor of barothermal treatment, pressed (a) at 120 °C, (b) at 140 °C.

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**Figure 5.** Dependence of water absorption for 24 hours of a thermowood composition on its density, pressed (a) at 120 °C, (b) at 140 °C.

### 4. Conclusion

Barothermal treatment of birch wood in a saturated steam media, accompanied by explosive decompression of the system, causes hydrolytic and structurally destructive changes in wood tissue. At the same time, there is a tendency to decrease the density of wood with an increase in the hardness factor ($R_0$) of the barothermal process. Hot pressing of hydrolyzed wood leads to its significant compaction, the degree of which, in addition to the pressing conditions, is determined by the temperature and duration of the barothermal action on the wood. The results of hot pressing of
hydrolyzed wood at temperatures of 120 °C and 140 °C does not display significant differences. In both cases, the region of conditional "saturation", at which a substantial increase in the density of the material is no longer observed, corresponds to a value of $R_0 \sim 3000 \text{ min.}$

Along with an increase in the density of the samples obtained under the conditions of rigidity of the barothermal treatment up to $R_0 \sim 2500 \text{ minutes}$, a proportional increase in the strength parameters of the thermowood composition is also characteristic. The $R_0$ increase over 2500 min. entails a sharp decrease in the strength characteristics of the material, due to the intensification of the processes of destruction, their dominance over the processes of formation of chemical bonds between the components of the wood complex. The water absorption of the material decreases in proportion to the increase in its density. There is a linear relationship between density and water absorption.

Barothermal treatment of birch wood to obtain on its basis a thermowood composition with optimum physicomechanical characteristics is expedient under the conditions of a process stiffness factor of no more than 2000...2500 min.

References

[1] Forests of the USSR. 1969 Forests of the Urals, Siberia and the Far East [in Russian – Lesa SSSR. Tom 4, Lesa Urala, Sibiri i Dal'nego vostoka] vol 4 (Moscow: The science) p 768
[2] Buglaj B M 1973 Wood finishing technology [in Russian – Tekhnologiya otdelki drevesiny] (Moscow: Forest industry) p 304
[3] Prieto Dzh and Kine Yu 2008 Wood. Processing and decoration [in Russian – Drevesina. Obrabotka i dekorativnaya otdelka] (Moscow: Paint-media) p 392
[4] Skuridin Yu G 2000 Structure and properties of composite materials obtained from waste wood after the explosive hydrolysis [in Russian – Stroenie i svojstva kompozicionnyh materialov poluchennyh iz othodov drevesiny posle vzryvnogo gidroliza] p 135
[5] Skuridina E M 2006 Development of technology of composite materials based on wood and polymer fillers [in Russian – Razrabotka tehnologii kompozicionnyh materialov na osnove drevesiny i polimernyh napolnitelej] Dissertation, Altai State Technical University p 170
[6] Overend R P, Chornet E and Gascoigne J A 1987 ‘Fractionation of lignocellulosics by steam-aqueous pretreatments [and Discussion]’ Phil. Trans. R. Soc. Lond 321 pp 523-536 DOI: 10.1098/rsta.1987.0029
[7] Chornet E and Overend R P 1988 Phenomenological Kinetics and Reaction Engineering Aspects of Steam. Aqueous treatments. Proceedings of the International Workshop on Steam Explosion Techniques Fundamentals and Industrial Applications pp 21-58
[8] Steam Explosion Pretreatment of Cotton Gin Waste for Fuel Ethanol Production by Tina Jeoh 1998 Thesis submitted to the Faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Biological Systems Engineering APPROVED: Foster A. Agblevor, Jiann-Shin Chen, Richard F. Helm, John V. Perumpral, December, p 137
[9] Startsev O V, Salin B N and Skurydin Yu G 2000 Barothermal hydrolysis of wood in presence of mineral acids Reports of the Academy of Sciences [in Russian – Doklady Akademii nauk] 370 5 pp 638-641
[10] Zhengdao Yu, Bailiang Zhang, Fuqiang Yu, Guizhuan Xu and Andong Song 2012 A real explosion: The requirement of steam explosion pretreatment Bioresource Technology 121 pp 335–341