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PROPERTIES OF HORNBEAM (*Carpinus betulus*) WOOD THERMALLY TREATED UNDER DIFFERENT CONDITIONS

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ABSTRACT

Hornbeam (*Carpinus betulus*) wood is not widely used in woodworking industry at present. Mechanical, physical and aesthetical properties of hornbeam wood as a material for furniture or joinery products can be improved by thermal modification. Heat-treatment technology was carried out under different conditions: temperatures of 160, 190 and 220 °C and time of 1, 10 and 20 hours. The influence of heat treating on physical (density, colour, moisture absorption and volume shrinkage), mechanical (compression strength along, across fibres and bending strength) and technological (impact resistance and wear resistance) properties of hornbeam wood were investigated. Analysis of physical and mechanical properties of hornbeam wood heat-treated for different time allowed researchers to determine optimal parameters of thermal modification: temperature of 190 °C and duration for 8–12 hours. It was found that the effect of high temperature on the technological properties of hornbeam wood is insignificant.

Key words: hornbeam wood, heat-treatment technology, colour, mechanical and physical properties.

INTRODUCTION

Hornbeam (*Carpinus betulus*) is not widely used species because the wood is heavy, prone to warping and moisture change. In addition, it has an inexpressive grey colour and a vague texture. Similar to many other wood species, hornbeam, despite its high mechanical strength and low thermal expansion, is hygroscopic and vulnerable to biological attack (ATES *et al.* 2009, SRINIVAS and PANDEY 2012). One of the ways to improve the properties of wood, except the use of chemical harmful substances (HILL 2006) such as acetylation or the introduction of furfural, is the process of thermal modification.

Significant studies in the field of wood thermal modification were conducted in many countries since the beginning of previous century (TIEMANN 1915, STAMM *et al.* 1946, THERMOWOOD HANDBOOK 2003). There are several basic technologies of wood heat treatment, that include heating of dry or wet wood at high temperatures in different environments, e.g. «ThermoWood» (Finland) in a steam environment; «Retification» (France) in the nitrogen environment; «Le Bois Perdure» (France) in a mixture of water vapour and gases emitted from wood; «Oil-Heat-Treatment» (Germany) in the environment of hot vegetable oils. The difference between these processes is the application of different temperatures (160–250 °C) and the environments (ALÉN *et al.* 2002, CALONEGO *et al.* 2010).

Under the influence of high temperatures, ecological material with modified properties is obtained. So, the dimensional stability and biological stability increase as a result of heat treatment but mechanical parameters of wood decrease (ESTEVES and PEREIRA 2009, AKYILDIZ *et al.* 2009). At the same time, modified wood acquires a rich colour change throughout the thickness of the material (DZURENDA 2018a). Such changes occur as a result of chemical transformation of wood structural elements. Cellulose and lignin break down more slowly than hemicellulose. Extractives partially and faster evaporate from wood during the heat treatment. Due to the decomposition of hemicellulose, the resistance of thermally treated wood increases against the impact of biological attack. The degree of chemical transformation of wood, that lead to achievement the desired colour, depends on the schedule of heat modification (VIDHOLDOVÁ *et al.* 2019). As wood is a natural polymer material, the process of thermal transformation is a series of chemical reactions of all structural components: cellulose, hemicellulose and lignin (GEFFERT *et al.* 2019). Heat modification schedule parameters have been proposed for different wood species, in particular, pine, eucalyptus (ESTEVES and PEREIRA 2009), birch and aspen (KOCAEFE *et al.* 2008), fir (KOL 2010), maple (KORKUT *et al.* 2008), poplar, ash, oak (HILL 2006) and their influence on the change of properties have been investigated so far..

The aim of this research is to determine the impact of different heat treatment schedules on the change of physical and mechanical properties of hornbeam wood, which can expand the ways of its use.

MATERIAL AND METHODS

Material

Hornbeam (*Carpinus betulus*) lumber from Zhytomyr region of Ukraine was used with the cross section of 30 × 100 mm and the length of 1000 mm. Before the heat treatment, lumber was dried in a drying kiln to the moisture content W = 8 %. Test pieces of standard sizes with no defects were cut from dried timber in quantities according to standard testing methods (quantity is specified for one processing schedule):

20 × 20 × 30 mm, 16, 121, 26 samples – to determine the basic density, shrinkage, compression strength parallel and perpendicular to the fibres,
20 × 20 × 10 mm, 16 samples – moisture absorption,
20 × 20 × 300 mm, 35 samples – modulus of rupture,
20 × 20 × 150 mm, 23 samples – wood impact resistance,
50 × 50 × 20 mm, 40 samples – wear resistance,
90 × 5 × 300 mm, 3 samples – colour.

To determine the influence of the schedule parameters of thermal modification on the change in the wood characteristics, the effect of which determines the scope of its use, the physical-mechanical and technological properties of the obtained material are determined according to standard methods: basic density (ρ_{bas}, kg/m^3) (GOST 16483.1-84 1985), indicators of shrinkage (β_{rad}, β_{tang}, %) (GOST 16483.37-88 1990), the amount of moisture absorption (U_{abs}, %) (GOST 16483.19-72* 1974), bending strength (*MOR*, MPa) (GOST 16483.3-84 1985), compression strength along and across fibres ($\sigma_{||}$, $\sigma_{\perp}$, MPa) (GOST 16483.10-73 1974, GOST 16483.11-72 1973), impact resistance (H, J/cm^2) (GOST 16483.16-81 1983), wear resistance (t, %) (GOST 16483.39-81 1983).

Methods

Hornbeam samples were modified at temperatures of 160, 190 and 220 °C with different duration of 1, 10 and 20 hours and used for determination the effect of high temperatures on the change of wood properties. The process of wood heat modification includes the processes of drying and the subsequent removal of bounded moisture leading to physical and mechanical transformations. These transformations affect the decomposition of wood structural components, what is the reason for the change of colour. In order to evaluate wood colour characteristics, there is used a colour determination system of *L*, *a*, *b* components (DOMASEV and HNATIUK 2009). By scanning the samples and identifying using Photoshop, the overall colour difference ΔE is determined:

$$\Delta E = \left(\Delta L^2 + \Delta a^2 + \Delta b^2\right)^{1/2} \tag{1}$$

where: ΔL^2 – square of the difference in the colour lightness of heat-treated wood samples relative to the sample without processing,
Δa^2 and Δb^2 – the square of the difference in chromatic parameters describing the ratio of green to red and blue to yellow components of colour.

The Arrhenius equation is traditionally used to determine the temperature dependence of the chemical reaction speed coefficient. The area of its application has considerably expanded, including the process of wood drying (SHI 2006, ZAREA-HOSSEINABADI *et al.* 2012, SOKOLOVSKYY and SINKEVYCH 2016). The use of the so-called "Arrhenius kinetics" is proposed to calculate the rate of wood decomposition, $\frac{d\omega}{d\tau}$ at known heating rate, the initial moisture content of the wood, in the case of the assumption that the degree of matter decomposition, ω, is the result of the wood mass loss (STILLER 1989):

$$-\frac{d\omega}{d\tau} = A_n \cdot e^{-\frac{M_\omega}{T_r}\cdot\tau_r} \tag{2}$$

where: A_n – coefficient considering the density of wood,
T_r – temperature,
τ_r – time of treatment,
M_ω – wood mass loss:

$$M_\omega = \frac{m_{in} - m_{cur}}{m_{in} - m_{fin}} \tag{3}$$

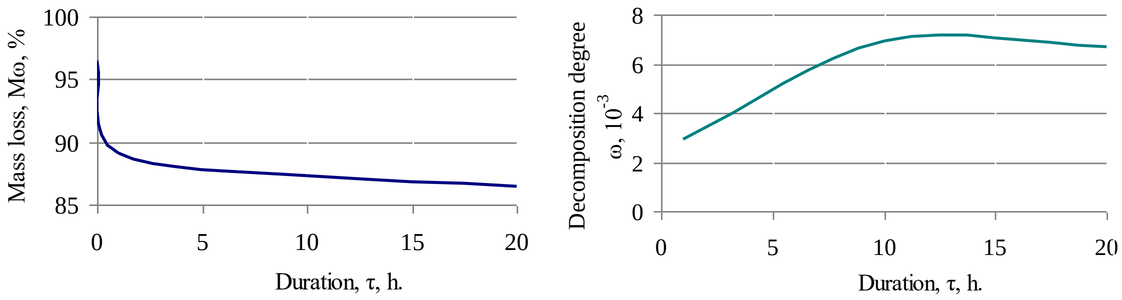
where: m_{in}, m_{cur}, m_{fin} – the initial, current and final wood mass.

Partial solution of the equation (2) with initial conditions $\omega_{in} = 0$, $\tau_{cur} = 1$ is:

$$\omega = \frac{A_n \cdot T_r}{M_r} \cdot \left(e^{-\frac{M_\omega}{T_r}\cdot\tau_r} + 1 \right) \tag{4}$$

RESULTS AND DISCUSSION

Calculations based on the results of previous experiments of mass loss determination by the equation (3) and the degree of decomposition (4) for the influence of temperature 160 °C for 20 hours showed that an increase in the decomposition of anatomical elements (Fig. 1) is associated with a mass change.



a b

Fig. 1 Decomposition of hornbeam wood under the high temperature influence in time: a – mass loss; b – decomposition degree.

Thus, by fixing the mass of samples during heat modification, a change in colour influenced by the degree of anatomical elements decomposition can be observed. Moreover, the loss of wood mass is one of the most important characteristics of heat treatment and it is usually called quality index (ESTEVES and PEREIRA 2009).

It is known that the change in the properties of wood during its thermal modification is influenced by the temperature and treatment duration. Changes in the structure of wood begin under the influence of temperature of 120 ºC (HILL 2006) and result from decomposition of hemicellulose. Lignin is more resistant to temperature influence, decompose begins at the temperature of 230 °C. These processes cause changes in wood properties. In general, in all existing wood heat treatment schedules, the temperature parameter is in the range of 160–280 °C (RAPP 2001).

The processing time for most schedules is within 10–52 hours (RAPP 2001). During the previous experiment, the fact that the effect of temperature duration of more than 20 hours on the properties of heat-treated hornbeam wood is practically not noticeable was found. Therefore, the range of temperature influence duration on wood is chosen within 1-20 hours. Influence of selected schedule parameters on hornbeam wood mass loss is illustrated in Fig. 2.

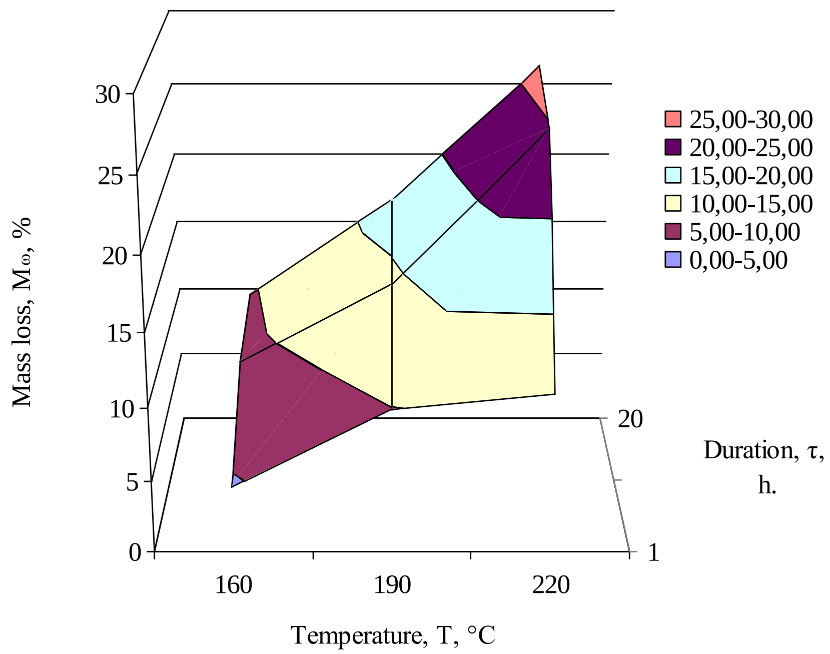


Fig. 2 Dependence of hornbeam wood samples mass loss after heat treatment.

Mass loss of samples after heat treatment is associated with a decrease in density of thermo-modified hornbeam wood (Fig. 3).

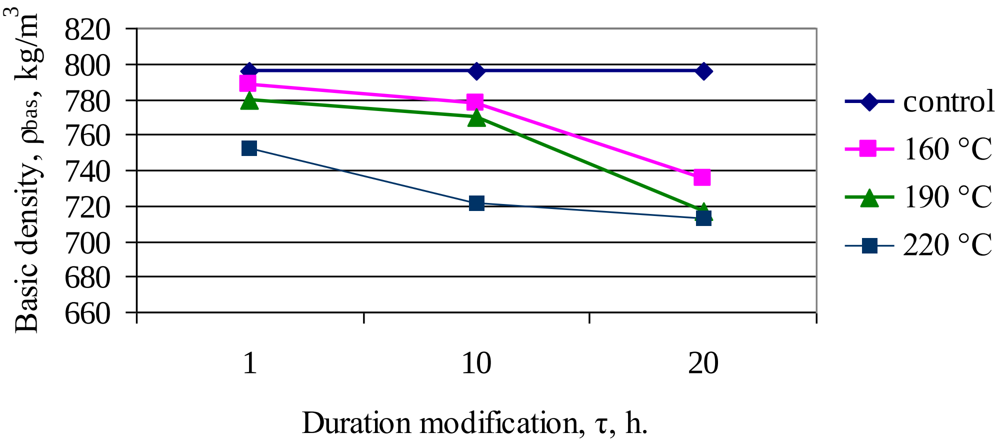


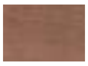
Fig. 3 Change of hornbeam wood basic density in relation to parameters of heat treatment.

A significant mass loss of 26% was found for samples processed at the temperature of 220 °C for 20 hours (hard schedule). In this case, the basic density of these samples decreased by 12%, samples treated at the temperature of 160 °C by 8%, and at 190 °C by 11%. A similar trend is observed in the results of other researchers (GÜNDÜZ *et al.* 2008; BAL 2014, SOPUSHYNSKYY *et al.* 2017) in the analysis of a decrease in density of alder by 5.6%, fir by 4.5% compared to untreated wood (KOL 2010). This is due to the degradation of wood polymers, mainly hemicellulose, which is the most thermally sensitive wood component (PONCSAK *et al.* 2006; YILDIZ *et al.* 2006).

Samples of untreated and thermo-modified hornbeam wood were used to determine the change of wood colour under the influence of high temperatures. The final colour of the wood was measured after stabilization of samples in room conditions for 24 hours. Test samples were scanned at the same illuminating conditions in order to avoid the occurrence of an error associated with the peculiarities of falling light. The resulting photos were processed using the Photoshop program and received components of the colour model *L*, *a* and *b*. Every colour in the model is determined by the brightness value *L* (Lightness) and two chromatic coordinates *a* and *b*. Results of measurements and calculations are given in Tab. 1.

It can be seen that during heat modification, the test pieces changed their colour across the depth according to the chosen schedule parameters and acquired colour typical for exotic wood species. It has been established that darkening of the colour (decrease of parameter *L* and increase ΔE) becomes more noticeable with increasing temperature and processing duration (KÚDELA AND ANDOR 2018). Reduction of the parameter *L* indicates that components absorbing visible light formed in the heat treatment process (AKSOY *et al.* 2011, DUBEY *et al.* 2012, ESTEVES and PEREIRA 2009, MITSUI *et al.* 2001, DZURENDA 2018b). At high temperature modifications, the samples are virtually black. The darkening of the colour may be due to the decomposition of hemicellulose with a simultaneous increase in the lignin fraction (KAMDEM *et al.* 2002). An exception is a sample No. 3 (ΔE = 13.9), the reason for this can be the oxidation of the wood surface in the air before the heat modification beginning.

Tab. 1. Results of colour components determination for heat-treated hornbeam wood.

Schedule No.	Modification schedule parameters		Colour parameter					
	Treatment temperature (°C)	Treatment duration (h)	Visualization of hornbeam wood colour changing after heat treatment	Sample colour after treatment	Results of measurements			Calcu-lated value
					L*	a*	b*	ΔE
1	Control			natural	58.4	12	16.4	–
2	160	1		oak kraft	53.2	15	18.6	6.8
3		10		alder mountain	46	17.6	18.8	13.9
4		20		light beech	48.4	14.4	17.4	10.5
5	190	1		oak stone	49.4	16.8	20.2	11.2
6		10		oak rustic	34.6	16.2	16.8	24.3
7		20		beech chocolate	25.2	11	10.8	33.8
8	220	1		walnut tiepolo	30.2	12.8	11.8	28.6
9		10		wenge	14.4	4.8	2.8	46.6
10		20		wenge louisiana	13.8	4.4	2.2	47.5

Note. The table shows the mean values for five points on each sample

The effect of high temperature modification on the change of moisture absorption of hornbeam wood is shown in Fig. 4.

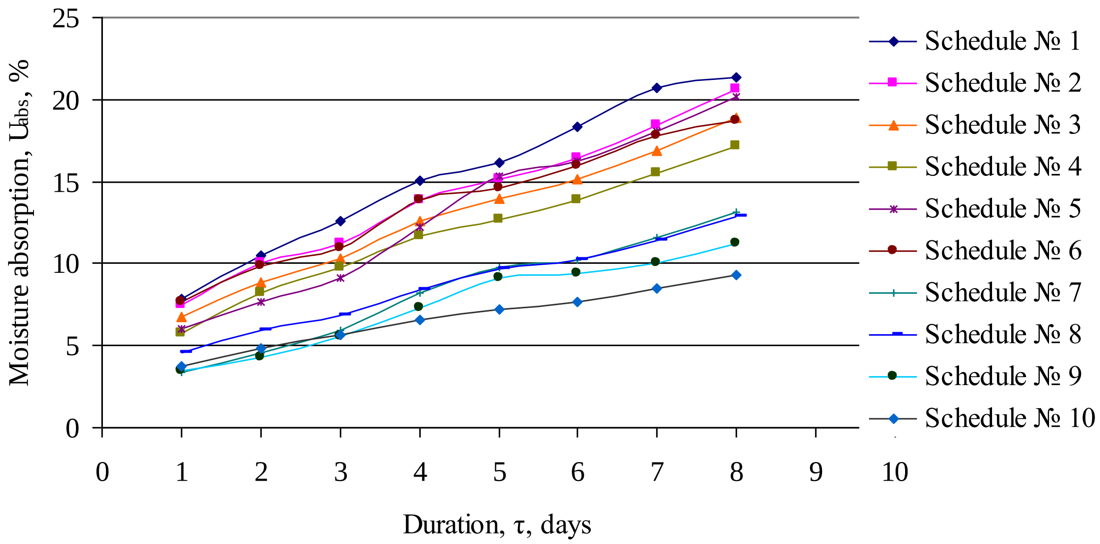


Fig. 4 Change of the moisture absorption of hornbeam wood after heat treatment.

The measured moisture content of samples at room conditions is 21.4% for untreated hornbeam wood and 9.3% for wood treated under maximum hard conditions. It was established that an increase in the treatment duration helps to reduce the ability of wood to absorb humidity from the air. Thus, when processed at a temperature of 220 °C, with an increase in the duration of treatment from 1 to 20 hours, moisture absorption is reduced by 1.4 times, when processed at a temperature of 190 °C by 1.5 times, and at 160 °C by 1.2 times. A similar tendency in reduction of moisture absorption is observed in the case of heat modification of eucalyptus wood (CADEMARTORI *et al.* 2014), acacia (VAN CHU 2013), juniper (KASEMSIRI *et al.* 2012) and black pine (DÜNDAR *et al.* 2012). The reason for the decrease of hygroscopicity can be explained by a decrease of quantity of hydroxyl groups in heat-treated wood (PETRISSANS *et al.* 2003). Also, reduction the water-sorption capacity of heat-treated hornbeam wood can be associated with a decrease in the number of primary sorption centres (–OH groups) within the framework of a wood cell wall, mainly as a result of decomposition and removal hemicellulose components from the wood (pentosanes).

The amount of volume shrinkage was determined as a change in the samples linear dimensions of heat modified wood after drying in a drying chamber at the temperature of 103 + 2 °C. Shrinkage reduction (Fig. 5) leads to improved dimensional stability of heat treated wood, expressed as an Anti-Shrink Efficiency (ASE).

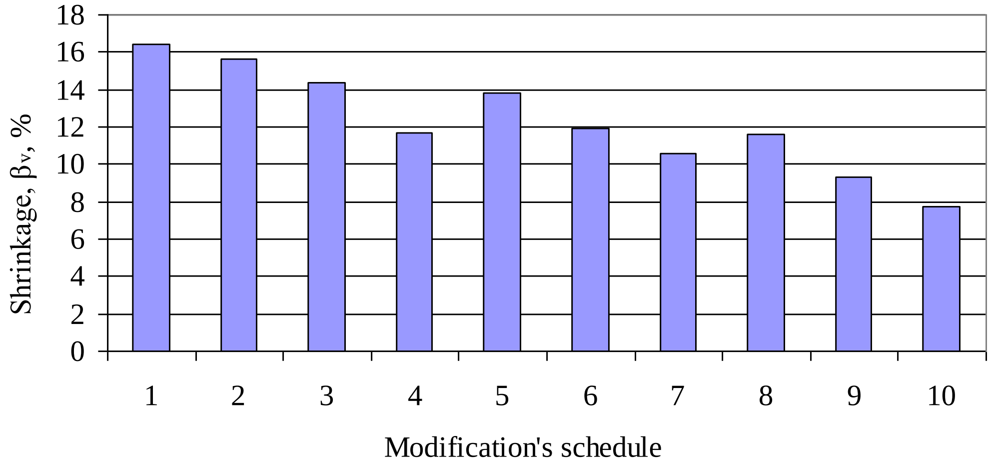


Fig. 5 Shrinkage in both transverse directions of samples of heat-treated and untreated hornbeam wood.

The heat treatment of hornbeam wood has led to an improvement in the stability of the sizes by reducing the volume shrinkage in 1.3–1.9 times. It is noted that with increasing temperature and processing duration the amount of shrinkage decreases, although the value of this indicator is influenced by the technology of heat modification (YILDIZ 2002, KAYGIN *et al*. 2009, AKYILDIZ *et al*. 2009, ESTEVES *et al*. 2007).

The effect of the change of mechanical properties of heat modified wood was investigated during compression tests along the fibres, across the fibres and the bending strength.

Compression testing of samples along the fibres showed that there was a grinding of the ends of samples of untreated wood (Fig. 6a). In samples heat-treated at a temperature of 160 °C, a sloping fold appears, placed at an angle of 45° (Fig. 6b). In the ruined hornbeam wood samples heat-treated by hard schedules No. 6 and No. 9 (Fig. 6 c, d), two opposing straights of the fold, forming a wedge-shaped area with a longitudinal split, are clearly noticeable. Samples of untreated hornbeam wood withstood a load of 34 kN, heat-treated with soft schedules 36–42 kN and hard schedules 34–47 kN.

a b c d

Fig. 6. The result of compressive strength along fibres of untreated and thermo-modified hornbeam wood samples for 10 hours: a – untreated wood, b – temperature 160 °C, c – temperature 190 °C, d – temperature 220 °C.

Heat treatment increases the fragility of the material (Fig. 6 c, d). This is confirmed in the work of researchers (BOONSTRA *et al.* 2007, ZAWADZKI *et al.* 2013, ANDOR and LAGAŇA 2018).

The results of the compression test across the fibres of hornbeam unprocessed wood samples and heat modified by soft schedules (No. 2, 3, 5) showed that they withstand a load of 5 kN without visible destruction. The samples which are heat modified at a temperature of 190 °C withstands the maximum load of 1.5 kN, and at 220 °C for 10 hours 1.1 kN, for 20 hours 0.9 kN with signs of destruction. During the test of bending at one-point load, the maximum load without signs of destruction was for hornbeam rough wood – 3.2 kN, heat modified for different times at a temperature t = 160 °C – 3.5–3.6 kN; at a temperature of 190 °C – 2.3–4.7 kN; 220 °C – 1.7–2.9 kN.

The influence of the heat modification of hornbeam wood on mechanical properties showed mixed results. Calculated values of the strength of samples treated by schedules No. 2 – 10 for different types of tests are shown in Fig. 7.

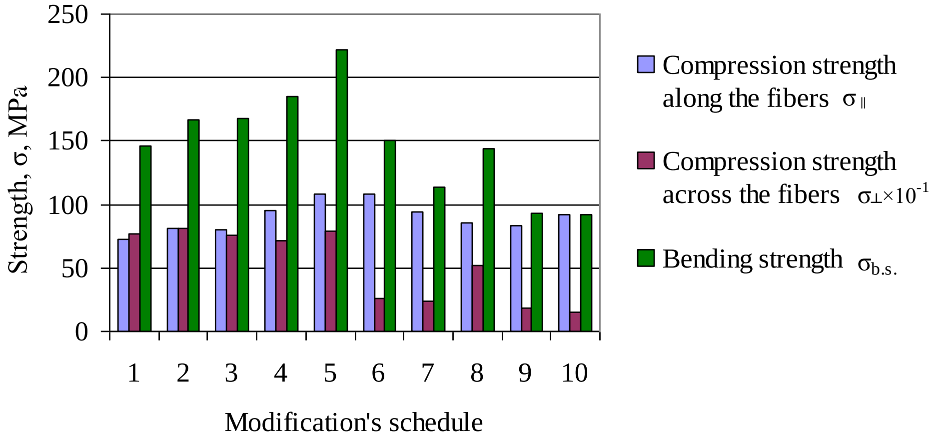


Fig. 7 Results of mechanical tests of untreated and heat modified hornbeam wood by different schedules.

It was found that the compressive strength along the fibres of hornbeam wood samples modified at 190 °C increased 1.3 times; samples treated at temperature of 160 °C show a significant decrease in the compressive strength limit across fibres 3.3 times at the temperature of 190 °C and 5.2 times at 220 °C. A similar loss of compressive strength across the fibres was recorded by MOLINSKI et al. (2018) for ash wood – 1.5 times. However, for the pine (BOONSTRA *et al*. 2007), this indicator increased by 1.07 times. Such differences are related to the anatomical structure of wood, in particular, with the peculiarities of the structure of perforations in the vessels of hornbeam wood and the absence of them in ash wood.

Bending strength slightly increased by 10-20 MPa after treatment at a temperature of 160 and 190 °C and preferably in the samples processed within 1 and 10 hours. A noticeable decrease in strength 1.6 times was observed at 220 °C at the modification within 20 hours. Several studies have found that heat treatment reduces the bending strength from 1% to 72% (JOHANSSON and MOREN 2006, ESTEVES and PEREIRA 2009, SHI *et al.* 2007, KORKUT 2008). The reasons for such change of mechanical properties have been widely discussed and it has been found that reasons for reducing the strength under bending and the destruction of the samples are decomposition of hemicelluloses and crystallization of amorphous cellulose.

Impact resistance of the wood is characterized by the size of the imprint (Fig. 8), which remains on the wood sample surface from a steel ball of 65 g, which freely falls from a height of 500 ± 1 mm counting from the bottom point of the ball surface. Carried out experimental studies showed that the modification of wood practically did not affect the index of impact resistance, there is a slight increase from 10 to 13% on the radial and tangential surfaces during modification at temperatures of 160 and 190 °C. During the modification at 220 °C, the impact resistance decreased by 9% only for the radial surface. It is worth noting that, as in untreated wood samples, the thermo-modified tangential surface is more resistant to impact than the radial.

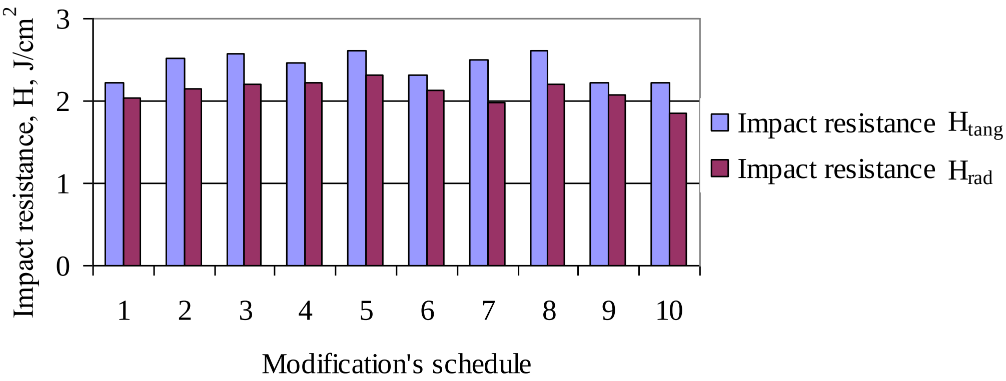


Fig. 8 Change of impact resistance values of hornbeam wood after heat modification.

Similar ambiguous results were observed when determining the impact resistance of heat modified wood of exotic species by Yank scale (ARAÚJO *et al.* 2016), pine and birch by Brinell (KYUNG-ROK WON *et al.* 2012), pine and oak by Shor (KARAMANOGLU and AKYILDIZ 2013). While the Thermowood Association of Finland noted increasing impact resistance with increasing temperature (THERMOWOOD HANDBOOK 2003).

The wear resistance of the material characterizing the ability of the surface layers to withstand fracture friction is one of the indicators for durability of hornbeam wood floor coverings. The results of wear resistance from experimental studies (Fig. 9) were evaluated by the weight loss value after grinding carried out in accordance with the requirements of GOST 16483.39-81 at the relative humidity in the room φ = 65 ± 5% and the temperature of 20 ± 2 °C.

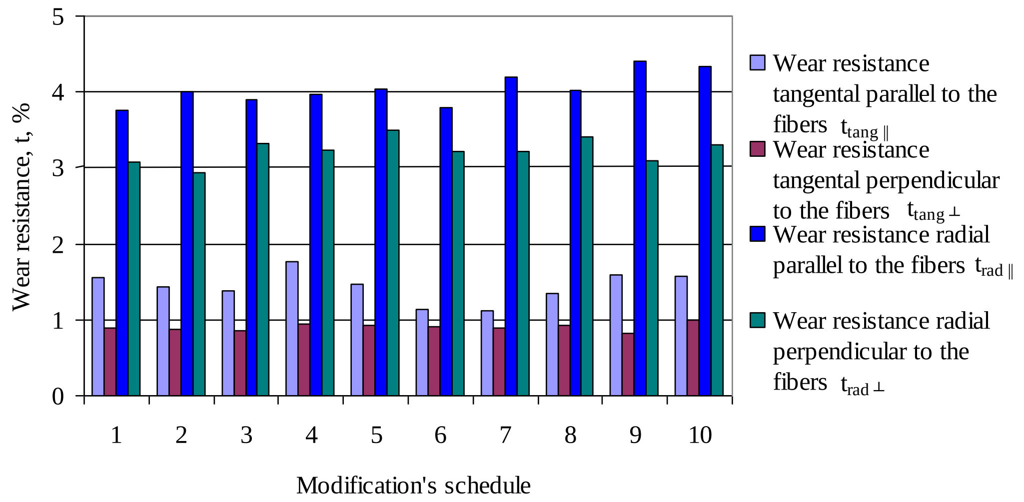


Fig. 9 The value of wear resistance in different directions for untreated and heat modified hornbeam wood by proposed schedules.

The analysis of obtained results did not reveal the effect of used schedules on the change of the wear resistance of hornbeam wood. It can be seen, that the wear resistance along and across fibres is better 2-3 times on the tangential surface of test pieces in comparison with the wear resistance on the radial surface. Similar results were obtained during the study of wild cherry wood wear resistance (AYTIN *et al*. 2015).

The influence of the heat treatment schedule parameters on physical and mechanical properties of hornbeam wood was studied by complete two-factorial experiment. The obtained regression models (Table 2) were checked for the adequacy of the Cochran (Gcr) and Fisher (Fcr) criteria.

Tab. 2. Checking the adequacy of regression models for output parameters.

№	Output Parameter	Regression equation	G-criterion		F-criterion	
			G_{calc}	G_{table}	F_{calc}	F_{table}
1	Basic density (kg/m^3)	ρ_{bas} = 747.02-14.63X_1-23.06X_2+3.27X_1X_2	0.48	0.60	2.13	4.11
2	Shrinkage (%)	β_{tang} = 5.35-1.64X_1-1.06X_2-0.2X_1X_2	0.41	0.60	4.10	4.11
		β_{rad} = 6.43-0.73X_1-0.90X_2-0.17X_1X_2	0.39	0.60	4.00	4.11
3	Moisture absorption (%)	U_{abs} = 15-3.86X_1-1.75X_2-0.05X_1X_2	0.32	0.60	0.22	4.11
4	Compression strength along the fibres (MPa)	$\sigma_{\parallel}$ = 88.48+0.32X_1+5.12X_2-1.83X_1X_2	0.32	0.60	0.25	4.11
5	Bending strength (MPa)	$\sigma_{b.s.}$ = 146.71-28.53X_1-8.03X_2-18.08X_1X_2	0.38	0.71	4.46	4.49
6	Compression strength across the fibers (MPa)	$\sigma_{\perp}$ = 54.70-21.6X_1-11.75X_2-0.67X_1X_2	0.56	0.60	2.72	4.11
7	Impact resistance	H_{tang} = 2.45-0.11X_1-0.03X_2-0.09X_1X_2	0.33	0.67	2.15	4.38
		H_{rad} = 2.11-0.07X_1-0.09X_2-0.10X_1X_2	0.46	0.60	3.20	3.26
8	Wear resistance	$t_{tang \parallel}$ = 1.54+0.14X_1-0.07X_2-0.03X_1X_2	0.36	0.60	0.58	3.26
		$t_{tang \perp}$ = 0.93+0.03X_1+0.02X_2-0.001X_1X_2	0.31	0.60	0.35	2.87
		$t_{rad \parallel}$ = 4.08+0.07X_1+0.10X_2+0.09X_1X_2	0.30	0.60	0.23	2.87
		$t_{rad \perp}$ = 3.22+0.05X_1+0.13X_2-0.10X_1X_2	0.49	0.60	1.07	2.87

Note. X_1 – temperature, X_2 – duration in normalized values

Since the conditions for inequality are fulfilled, the models are accepted as adequate and can be used to describe the output parameters. The verification of the regression equations adequacy for impact resistance and abrasion has shown that the models are adequate, but the regression coefficients X_1, X_2 and X_{12} are not significant, correlation connection is also not established. That is, the heat modification of hornbeam wood does not affect these properties.

The obtained equations can be used to determine rational schedule parameters. There are many methods to find the best solutions with certain features: the alternate variation of each input variable – the long-term path to finding the optimum (the Gauss-Seidel method); the large number of variables (random search method); the difficulty in selecting the value of the step of the factor change (gradient optimum search method); the gradual transition from the consideration of the influence of the most powerful factors to insignificant (relaxation method). The method of steep climb combines the listed methods and the method of a full-factor experiment. It can be applied to nonlinear mathematical models. The essence of this method is the systematic movement towards the fastest growth or decline of the output variables, with the direction corrected when the partial extremum of the target function is achieved (SKYBA *et al*. 2010).

In our case, the target function was implicitly expressed, although it outlined the schedule parameters in which the properties studied acquire a partial extremum. The application of the steep climb method allowed determining the rational regime parameters of the heat modification of hornbeam wood (Fig. 10).

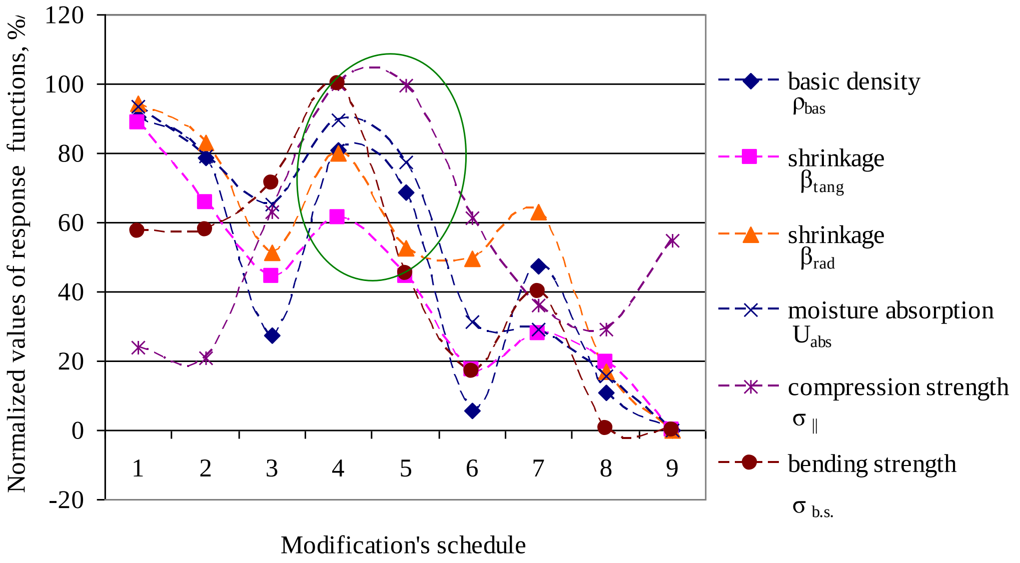


Fig. 10 The area of rational schedule parameters for heat modification of hornbeam wood.

It can be seen that the best results of the investigated physical and mechanical properties of heat modified hornbeam wood can be achieved with the following schedule parameters – temperature t = 190 ° C and duration in the range τ = 8-12 hours.

CONCLUSIONS

The research established that the process of heat treatment of hornbeam wood occurred with the mass loss depending on the degree of decomposition of anatomical elements. A simplified Arrhenius equation was proposed to describe and calculate the degree of phased decomposition taking into account the mass loss of structural components of wood at each stage of the process. The fact that with increasing temperature and treatment duration, the mass loss of hornbeam wood increases from 4.5% to 26% in the case of heat treatment by different schedules was determined. The influence of schedule parameters of the heat modified process on the change in the value of some physical properties (density, colour, moisture absorption and shrinkage) of hornbeam wood was determined. The fact that in comparison to untreated wood, heat modified hornbeam wood: the density decreases by 8‒12% when applying different schedules accordingly; the moisture absorption decreases by an average of 2‒3.5 times when using hard schedules; the volume shrinkage decreases by 1.3‒1.9 times. Also, it was established that thermo-modification has the ambiguous effect on mechanical properties of hornbeam wood: the compressive strength across the fibers decreases by an average of 8‒80%; the compression strength along the fibres is improved by 10‒50%; the bending strength increases by 20‒50% in samples thermo-modified at temperatures of 160 and 190 °C, and then decreases.

Based on the analysis of theoretical and experimental data, rational schedules of heat modification of hornbeam wood were established with the help of step climb method. The best results of physical and mechanical properties of investigated hornbeam wood were achieved with the following heat treatment schedule parameters: temperature t = 190 °C and duration within the range τ = 8‒12 hours. Wood treated under such conditions contributes to a decrease in the shrinkage rates along and across fibres and moisture absorption values. The basic density decreases after heat modification, hornbeam wood becomes lighter at the same hardness. These parameters indicate the dimensional stability and such wood can be used in an environment with significant temperature and humidity variations. An increase in the static bending strength and compression along the fibres, as well as maintaining the resistance of the wood to abrasion, allow producers to use the heat-treated hornbeam wood for interior and exterior applications. After heat modification, the hornbeam wood acquires a colour that simulate some tropical species. Moreover, modified wood is much cheaper and does not require additional surface finishing and impregnation with protective substances and can be used for floor coverings, garden furniture and decor, the arrangement of terraces, playgrounds, etc.

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