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Modeling of the processes of the modification of the current volume warming by drainage and pressing

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Abstract

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This work creates and verifies a mathematical model for modifying soft-leaved wood by impregnation and compaction. The relevance of this work is because due to global climate change, recently there has been a change in the average formula of the species composition of many forests of the temperate zone of Eurasia: soft-leaved wood species replace the coniferous forests of natural generation. The change in species composition is aggravated by the active spread of plantation growing of forests, because soft-leaved wood species are more suitable for plantation growing. One of the most promising areas for processing soft-leaved wood, including those grown by plantation, is the modification of such wood by impregnation and compaction. The main technological processes of obtaining modified wood with the achievement of specified parameters and properties is the dehydration of samples impregnated with various compositions with simultaneous pressing and drying. As a result of the implementation of the developed mathematical model, an equation of linear multiple regression is obtained depending on the sample processing time on the required values of their compaction and humidity in a given temperature field, which forms a reliable theoretical basis for solving various optimization problems of the technological parameters of the pressing and dewatering plasticized wood samples.

Keywords: agricultural engineering; wood; drainage; pressing; optimization

Introduction

All over the world, including in Eurasian forests, significant changes are observed, primarily due to a change in the average formula of the species composition in favor of soft-leaved wood species, which replace the coniferous forests of natural generation (Irland et al., 2001; Brunt et al., 2006). The problem of changing the natural coniferous plantations with soft-leaf subsequent generations is connected with both natural and economic factors. Natural factors include, above all, a shorter duration of the age class and, accordingly, a higher growth rate of soft-leaved wood species, compared with conifers. Economic factors are related to the fact that soft-leaved wood is in low demand at woodworking enterprises (Bollmus et al., 2017; Mokhirev et al., 2018). Soft-leaved woods are practically not used for the manufacture of structural timber. On the other hand, there are some examples of the effective use of soft-leaved wood for the production of furniture blanks, wood-based panels, and fuel (Pettinari et al., 2017). The ever-increasing distance of the removal of harvested wood more and more raises the question of growing fast-growing tree species by the plantation method, followed by efficient processing into sought-after products (Vagveldi et al., 2016; Bobar & Winder, 2017). One of the most promising areas for processing soft-leaved wood, including those grown by plantation, is the modification of such wood by impregnation and compaction. The main technological processes of obtaining modified wood with the achievement of specified parameters and properties is the dehydration of samples impregnated with various compositions with simultaneous pressing and drying (Shamaev, 2003; Bollmus et al., 2017). In this work, it was developed a mathematical model of drying with pressing pre-impregnated with various wood compositions. In this model, the criterion of optimization and the target was the achievement of high quality indicators with the least expenditure of energy. It should be noted that in addition to the quality indicators achieved by optimizing the processing of soft-leaved wood, an important aspect is the energy intensity of these processes, which, especially recently, is becoming a matter of paramount importance in logging production (Gustavsson & Sathre, 2006; Bribián et al., 2011; Grigoriev et al., 2014).

Materials and Methods

Table 1 shows the values of $\alpha.10^{-6}$ (1/deg) (the coefficient of linear expansion of wood, which characterizes the increase in the unit length of the material when heated by 1°C) across the fibers in the radial and tangential directions for three wood species (Ugolev, 2001).

As follows from the data Table 1, for different types of wood, the coefficient α is observed in different directions across the fibers. Along the fibers, similar indicators are 7 to 10 times less than the data in Table 1, i.e. the temperature factor is more significant when pressing wood samples across the fibers.

Table 1. The coefficient of linear expansion of wood

Wood species	The coefficient α across the fibers in the direction	
	Radial	Tangential
Birch	27.9	33.7
Pine	29.7	31.3
Aspen	26.0	35.9

In Table 2, based on experimental data (Shamaev, 2003), the values of E_1 and E_2 for urea samples of birch of different humidity W, plasticized with urea, are presented. Note that depending on the value of W, the ratio, E_1/E_2 for example, in the radial direction, changes 1.7-4.7 times. In the same relation, at constant pressure, the deformations of ε_2 to ε_1 will also differ, however, it is generally wrong to neglect instantaneous elastic deformations.

Table 2. Instant and durable elastic moduli of impregnated birch

W, %	Elastic moduli, MPa in directions					
	Radial		Tangential		Along the fibers	
	E_1	E_2	E_1	E_2	E_1	E_2
10	1180	700	707	280	13120	7300
20	860	180	450	180	7320	4770
30	440	110	330	110	5270	3290

Table 3 shows the values of E along the fibers (E_f) and across the fibers in the radial (E_r) and tangential (E_t) directions (Wood calorific value table for all species, 2019). With the growth (decrease) of humidity by 1% of the value of E, it is necessary to reduce (increase) by 2%.

Table 3. Young‘s modulus E for natural wood samples

Wood species	E_f, MPa	E_r, MPa	E_t, MPa
Pine	1170	20	500
Spruce	1420	590	360
Oak	1400	1290	910
Birch	1580	600	450

Table 4 shows the data of the coefficient K_{sh} of drying of a number of wood samples across the fibers in different directions (Nilsson & Stenström, 2001).

Table 4. The coefficient of shrinkage of wood by direction

Wood species	K_{sh} (%)in the direction	
	Radial	Tangential
Pine	0.18	0.33
Spruce	0.14	0.24
Larch	0.22	0.40
Oak	0.18	0.28
Birch	0.26	0.31
Aspen	0.20	0.32

Results and Discussion

Considering the results of the factor analysis of the influence of pressing indicators on the properties of modified wood (Shamaev, 2003), let us take as the criterion of the efficiency of technological processes the final density ρ of the sample (or its relative compaction $\overline{\rho} = \rho/\rho_0$, where ρ_0 is the initial density of the impregnated wood before pressing) at a given degree $\overline{W}$ of its dehydration, i.e. reduce the initial moisture content W to the required level.

Let us consider the scheme of the applied technology of pressing rectangular samples of wood impregnated with moisture and saturated with a flat die *1* without using molds (Fig. 4, Fig. 1a). Let us assume that pressing a layer h of wood sample *2* with height H and width b is carried out across the fibers in the radial direction (direction of force P) with simultaneous drying in a given temperature field T. The degree of pressing of the sample or the value of the total longitudinal strain ε is related to the value $\overline{\rho}$ by ratio:

$$\overline{\rho} = \varepsilon + 1. \tag{1}$$

In this case, the condition for effective deformation of the sample without increasing its width b and destruction of wood *2* elements up to the specified values of pressing is the following requirement (Shamaev, 2003): during the necessary and sufficient time interval t_0 effective dewatering of the wood sample, pressing is carried out at such a speed of $V_n = h/\tau$, at which the total value of the total transverse strain ε_t of the marginal zone of sample *3* coincides with the amount of shrinkage strain ε_y across the fibers in the tangential direction, i.e. the condition is fulfilled:

$$\varepsilon_t = \mu\varepsilon = \frac{\nu}{(1-\nu)}\varepsilon = \varepsilon_y \tag{2}$$

$$V_{n\text{-}}V_p\varepsilon_y = \varepsilon_{sh}.$$

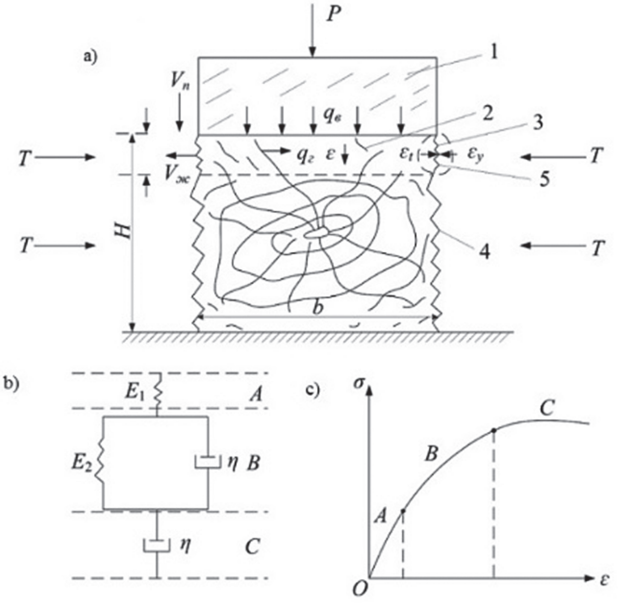

Fig. 1. Scheme of deformation of wood in the process of pressing and drying: *a*) model of the filtration body; *b*) model of the element of the environment; *c*) model of the deformation of the environment

The relation (2) denotes: μ – the coefficient of lateral expansion, ν – Poisson's ratio, ε is the total longitudinal deformation of the medium in the direction of pressing.

In practice, the specified range of pressing is mainly ε = 0.4–0.6, however, in some cases, the value of ε exceeds the upper limit of this range. Taking into account that the deformation of the sample occurs in the field of high temperatures (up to 140–170°C), relations (1) and (2) need to be refined, since temperature deformations ε_T and shrinkage deformation ε_{sh} have an additional effect on the values and ε_t. We assume that in a sample of wood heated to temperature T, temperature deformations ε_T act and the material experiences a corresponding internal pressure of P_T equal to (Parton, 2010):

$$P_T = E\varepsilon_T = \frac{\alpha ET}{2(1-\nu)}, \tag{3}$$

where E is Young's modulus, α is the coefficient of linear expansion of wood, which characterizes the increase in the unit length of the material when heated by 1°C.

Under the action of a compressive load P, the layer h experiences a vertical q_v and a horizontal q_h of pressure, equal to (Shapiro et al., 2006):

$$q_v = \frac{Eh}{R\mathrm{arctg}\left(\frac{H-h}{R}\right)}, \tag{4}$$

where R is the stamp parameter:

$$R = \frac{2b\left(1+\frac{b}{H}\right)}{\sqrt{\pi}},\ \mu = \frac{\nu}{(1-\nu)}..$$

In relation (4): μ is the lateral expansion coefficient, n – Poisson's ratio, E is Young's modulus.

The deformation of an arbitrary element of the medium can be described by generally accepted models (Blend, 1965).

In (Shamaev, 2003), the Maxwell and Burgers models with two values of stress relaxation time t_σ were used to study the deformation of impregnated wood. It is noted that elastic deformations in wood are determined by the presence of cellulose, and inelastic ones by lignin and hemicelluloses. For oak samples, the $t\sigma$ values t_σ for instantaneous elastic deformation are 14.35 s, for long-term deformation – 53.14 s. For birch samples, these figures are respectively 11.19 and 61.98 s.

The generalized four-element Voigt model (Fig. 1*b*), according to (Blend, 1965), describes well the process of deforming nitrocellulose without a successively attached first spring with an E_1 modulus of instantaneous elasticity thus, it is believed that the effect of instantaneous elastic deformations ε_1 can be neglected in comparison with long ε_2:

$$\varepsilon_1 = \frac{q_v}{E_1}; \ \varepsilon_1 = \frac{q_k}{E_2}, \tag{5}$$

where E_2 is the modulus of long-term elastic deformation.

The same model was used in the analysis of the processes of static compression by flat stamps of soil-grounds penetrated by the root tree system (Shapiro et al., 2008). It is shown that when describing the process of compacting the medium, it is advisable to combine two elastic elements into one with a common modulus of elastic deformation (Young's modulus) $E = E_1 + E_2$, i.e. the total elastic deformation in the deformation sections *A* and *B* (Fig. 1b,*c*) is the su:

$$\varepsilon_0 = \varepsilon_1 + \varepsilon_2. \tag{6}$$

Viscoplastic deformation ε_n, manifested in areas *B* and *C*, based on the results of research (Shapiro et al., 2008) can be defined as:

$$\varepsilon_p = \frac{E_1}{E_2}\left(1 - \mathrm{EXP}\left(-\frac{t}{t_l}\right)\right)\left(\ln\frac{h}{H} + 1\right) \tag{7}$$

where t_l is the lag time for the Voigt element, equal to the ratio of the viscosity η of the medium to the elastic modulus E_2 of the second spring.

Analysis of the creep curves ε(*t*) of nitrocellulose heated to 90°C (Blend, 1965), as well as birch samples (Shamaev, 2003) impregnated and heated to 99°C at different humidity values (*W* = 5–20%) and compression pressure (q_v = 1.8–8 MPa) showed that the value of t_l can exceed 300 s, and under certain conditions it reaches 600 s.

Since the value of *G*, the inverse of the elastic modulus *E*, is the elasticity of the elastic spring, in our case the time lag t_l is the product and the more viscous the medium, the larger the value of $t_l.t_{n-}t_{l.}$:

$$t_l = \eta G = \eta / E_2 \tag{8}$$

An increase in viscosity can be due to both an increase in the coefficient η and a decrease in the modulus of long-term elastic deformation E_2. With regard to the pressing process of impregnated wood, in particular urea (carbamide); this is achieved by increasing the percentage of plasticizer and its heating temperature.

During the entire period of deformation of the layer *h* in section *B* of stress growth σ and in section *C*, where σ = const (Fig. 1*c*), the total strain ε in the direction of pressing is estimated as the sum of elastic and viscoplastic deformations, i.e.

$$\varepsilon = \varepsilon_0 + \varepsilon_p. \tag{9}$$

Let us note one more circumstance. In the process of drying wood, as its moisture content *W* decreases, the E_i indices increase, i.e. the elasticity of elastic elements in the Voigt model decreases and the retardation time decreases, which must be taken into account when estimating ε_n using relation (7).

Let us compare data in Table 2 with data in Table 3, obtained by determining the Young's modulus *E* for various natural wood species at *W* = 15%.

Summing up the indicators E_1 and E_2 in Table 2 and extrapolating linearly the obtained value of *E* by the moisture index *W* = 15%, we compare the result with the generalized index *E* from Table 3. As a result, it can be concluded (by the example of birch samples) that the plasticization of wood leads to a tendency to increase the total modulus of elastic deformation *E*.

When the pressing wood, saturated with moisture to a depth *h,* is considered (Fig. 1a) an elastic filtration body, it is assumed that both the initial spring 4 and the compressed spring 5 of two combined elastic elements (Fig. 1b) contain micro holes through which fluid flows out according to the linear Darcy law (Kolesnikov et al., 2019).

As such holes (the main water-carrying elements of wood) take vessels or tracheids with a certain density of their placement of N_c (pieces per 1 mm^2 sample surface) and diameter d_c (μm). In particular, for birch (as a whole along the trunk), these values are N_c = 98 pcs/mm^2 and d_c = 58 μm, respectively.

We will assume that as the wood layer is pressed and the total longitudinal strain ε increases, the channel diameter dc decreases in proportion to 1-ε. Based on the methodological provisions, the condition is fulfilled in a fully saturated wood moisture:

$$q_v = p_w + p_{fl}, \tag{10}$$

where p_w is the pressure in the wood, and p_{fl} is the pressure in the liquid.

The value of p_w is determined by the values of the pressure of the vertical displacement h and the temperature expansion of the P_T:

$$p_w = \frac{h}{H}E + P_T. \tag{11}$$

Performing the necessary transformations, by analogy with (Chibirev et al., 2019), we obtain the integral-differential equation for the speed V_i of the immersion of the stamp:

$$\frac{1}{4\gamma}b^2 C_{sy} k_p \frac{d\ln V_p}{dt} = -\left(q_v + E + P_T\right) + 2\frac{E}{h}\int_0^t V_p dt, \tag{12}$$

where C_{sv} is the specific volume of the pore space in the volume of wood occupied by the liquid; k_p is the permeability coefficient of the medium (cross-sectional area of the channel of the porous medium through which the fluid is filtered); γ dynamic fluid viscosity.

$$s_c = \pi d_c^2/4. \tag{13}$$

The speed V_p is related to the velocity V_{fl} of the outflow of fluid through the spring holes by the integral relation (Chibirev et al., 2019):

$$V_{fl} = \frac{C_{sy} V_p b}{2\left(h - \int_0^t V_p dt\right)}. \tag{14}$$

The speed V_p is related to the velocity V_{fl} of the outflow of fluid through the spring holes by the integral relation (Chibirev et al., 2019):

$$V_{fl} = \frac{C_{sy} Vn}{2(H - h)} \mathrm{EXP}\left\{-\left(q_v + E + P_T\right)\frac{4k_p t}{\gamma C_{sy} b^2}\right\}. \tag{15}$$

Determining V_{fl} from (15), let us calculate the time to relaxation of dehydration during the outflow of a fluid within the layer h as:

$$t_0 = \gamma \frac{C_{sy} V_p b^2}{4p_n(q_v + E + P_T)}. \tag{16}$$

Then the size d_{dh} of the marginal area in layer h, in which the wood will dehydrate during the time t_o, is:

$$d_{dh} = V_{fl} t_0. \tag{17}$$

The degree (percentage) of dewatering $\overline{W}$ of the sample within its width b will be (Shamaev, 2003):

$$\overline{W} = \frac{2d_{dh}}{b} \tag{18}$$

The requirement to fulfill relation (2) in the process of pressing the layer h of wood dictates the need to determine the amount of deformation of shrinkage ε_{sh}. The value of ε_s depends on the coefficient of shrinkage of the wood K_{sh} and the degree of dehydration:

$$\varepsilon_{sh} = K_{sh}\overline{W}. \tag{19}$$

As follows from the data analysis Table 4 K_{sh} value varies in a fairly wide range of values, with shrinkage in the tangential direction for coniferous woods on average 1.7-1.8 times greater than shrinkage in the radial direction, whereas for hardwood this ratio decreases to 1.2-1.6.

Thus, it is advisable to press the wood in the direction of minimum shrinkage. If this factor can be considered insignificant for birch specimens, it is essential for other breeds (Tambi et al., 2017).

The purpose of the implementation of the adopted method of dewatering during the process of pressing and drying wood is to provide such conditions under which relation (2) is fulfilled and a sample is obtained with a given density and strength without the formation of cracks and defects.

Wood will be pressed cyclically in two stages:

- at the first at $0 \le t \le \tau$, the pressing pressure q_v increases to the maximum value in accordance with the given speed V_p;
- at the second, when $\tau < t \le t_o$, the pressing pressure is kept constant at the reached level.

The combination of relations (1)-(19) is the basis of a mathematical model of pressing samples of impregnated wood with their simultaneous drying. Calculations using these ratios were performed for pressing across the fibers in the radial direction under a flat press of specimens of heated moist birch impregnated with 10-20% aqueous urea solution, with the following initial data: $V_p = 1.4$ mm/min, $\alpha = 33.710^{-6}$ (1/degree), $W = 50\%$, $\rho = 760$ kg/m^3, $E_r = 126.9$ MPa, $E_t = 101.5$ MPa, $\nu = 0.3$, $T = 140$°C, $E_1/E_2 = 4$, $b = H = 0.13$ м, $К_у = 0.26$, $s_c = 0.00264$ mm^2.

In Fig. 2 for the first pressing stage, the dependences $q_v(h)$ and $t_o(h)$ are presented. As you can see, there is a linear increase in the values of q_v and t_o with increasing h. At the end of the first pressing stage ($\tau = 60$ s), the values of $q_v = 1.506$ MPa were achieved and the necessary and sufficient dehydration time was set $t_o = 543$ s.

Following the recommendations of (Shamaev, 2003), the best conditions for pressing wood with simultaneous drying are carried out at close temporal relaxation values of dehydration to and lag time t_l, and therefore in the counting process when determining deformations ε_d in accordance with relation (6) we withstand $t_n = t_o$. With an increase in the pressing time t at the first stage, a decrease in the moisture content W (Fig. 3*a*) of wood by an amount

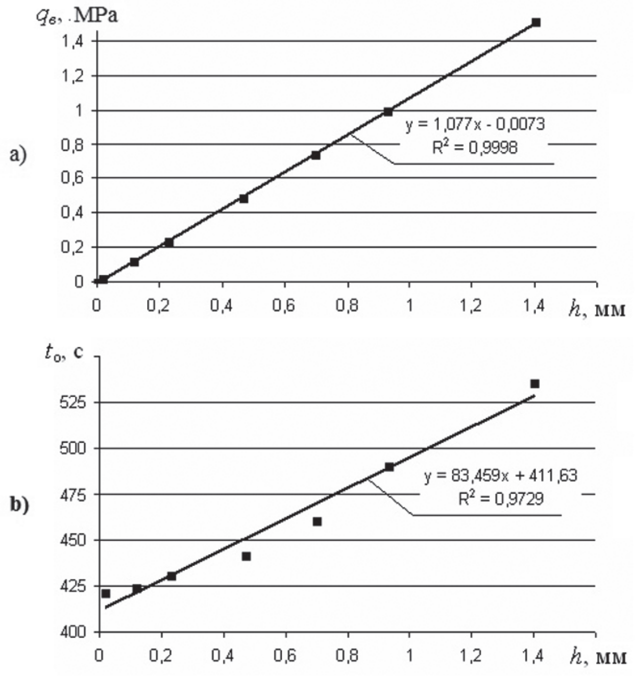

Fig. 2. The dependencies $q_v(h)$ and $t_o(h)$:
***a*) the magnitude of the compression pressure q_v (MPa);**
***b*) time of dehydration t_o (c)**

$$\Delta W = W - \overline{W}. \tag{20}$$

At the same time, the relative compaction of wood $\overline{\rho}$ (Fig. 3b) in the direction of compression is determined both by the value of the total longitudinal strain ε and additional deformations of the temperature expansion ε_T and shrinkage ε_{sh}:

$$\overline{\rho} = 1 + \varepsilon - \varepsilon_T + \varepsilon_{sh}. \tag{21}$$

As we see, only in two cases, the relation (21) coincides with the classical relation (1): either the temperature T is insignificant and, as a result, $\varepsilon_T = \varepsilon_{sh} = 0$ or the temperature deformations are significant and tend to shrinkage deformations, i.e. $\varepsilon_T \approx \varepsilon_{sh} \neq 0$. In all other cases, when $\varepsilon_T \neq \varepsilon_{sh}$, in the tangential direction the condition should be:

$$\varepsilon_t = \mu\varepsilon - \varepsilon_T = \varepsilon_{sh}. \tag{22}$$

Thus, data analysis in Fig. 2 and Fig. 3 allows us to conclude that the first stage of pressing and dewatering with simultaneous drying of wood samples is well described by linear deformation processes and the corresponding linear dependencies.

We investigate the fulfillment of condition (22) over the entire time interval of dehydration, i.e. Let us compare the behavior of the dependences $\varepsilon_t(t)$ and $\varepsilon_{sh}(t)$.

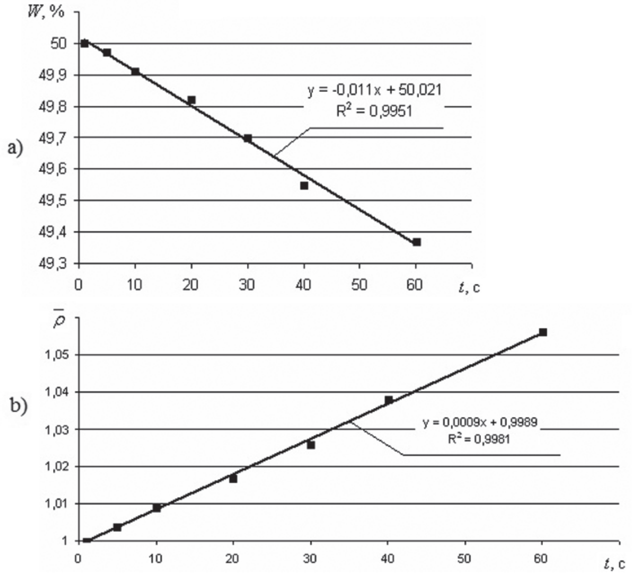

Fig. 3. The dependences of $W(t)$ and $\overline{\rho}(t)$ at the first stage of pressing: *a*) W(t); *b*) $\overline{\rho}(t)$

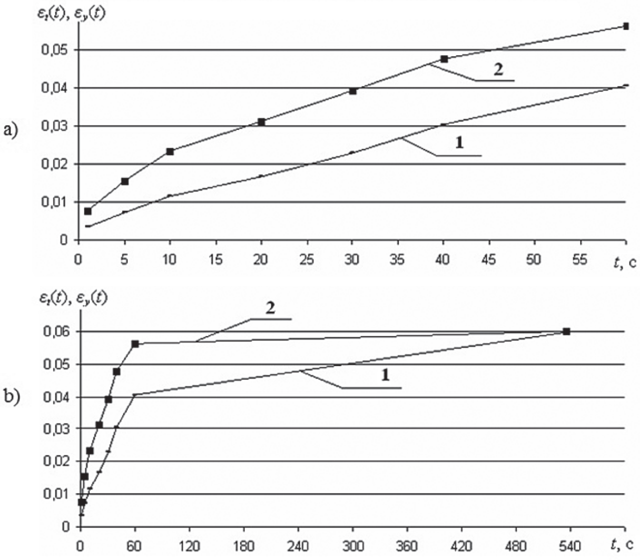

Fig. 4. The nature of changes in the processes of deformation of wood over time:
***a*) change in total transverse strain ε_t;**
***b*) change of deformation shrinkage ε_{sh}**

Fig. 4*a* shows the dependences of the change in total transverse deformation ε_t and deformation of shrinkage ε_{sh} on time t. As you can see, during the first stage of deformation of wood in a given mode, condition (17) does not hold and the inequality $\varepsilon_{sh} > \varepsilon_t$ holds, and by the time of completion of the stage ($t = \tau = 60$ s) the excess reaches 39%.

However, the second stage of pressing and drying the layer h of the wood sample is characterized by a reduction in the difference in deformation rates ε_t and ε_{sh} and by the time the stage is completed, condition (22) is fully met (Fig. 4b). In Fig. 5 by analogy with the data, Fig. 3 shows the graphs of changes in humidity and relative compaction of a given layer of wood during both stages with the observance of the pressing condition (22).

Comparative analysis of data in Fig. 3 and Fig. 5 shows that the linear nature of the dependences $W(t)$ and $\overline{\rho}(t)$ established for the first stage of deformation has changed to the general logarithmic law for describing these processes throughout both stages with satisfactory approximation figures of the calculated data (the coefficients of determination are 0.87-0.9).

In one cycle (step) of pressing and dewatering (t_o = 543 s), the relative compaction reached $\overline{\rho}$ = 1.085, i.e. the density of wood within the layer h = 1.4 mm increased from 760 to 825 kg/m^3, and the humidity decreased from 50 to 49.15%.

Next, it is necessary to produce a new cycle of pressing, dewatering and drying in accordance with the accepted technology of work and, ultimately, to obtain a sample of wood with given indicators of density and humidity.

The nature and intensity of deformation of the samples depend on a number of source data, namely: the conditions for placing the blanks in the molds, their initial moisture W_o, the concentration of the urea solution C and the increase in its mass Q, the methods of creating an overpressure P, the level of the specified temperature field T, and also on the shape and size of pressing tools (dies) in the process of their impact on solid wood.

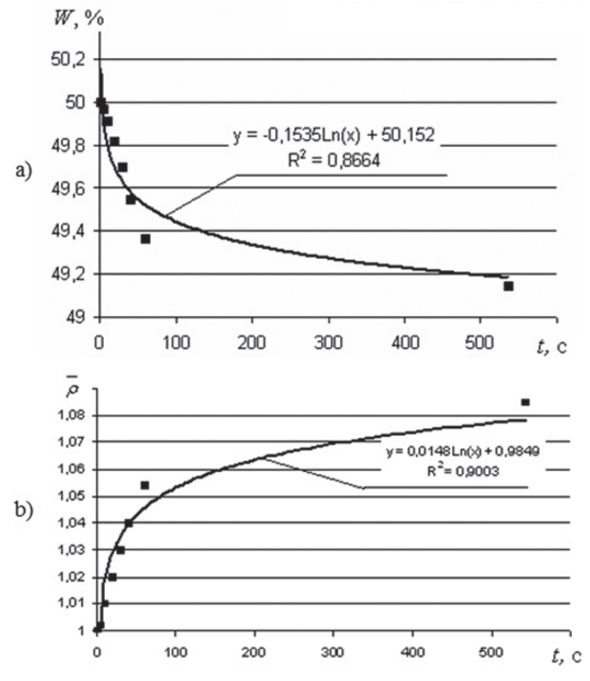

Fig. 5. Dependences of $W(t)$ and $\overline{\rho}(t)$ at both stages of pressing: *a*) $W(t)$; *b*) $\overline{\rho}(t)$

The main technological parameters affecting the final indicators of modified wood are: 1) pressing speed $V_n = h/\tau$, where h is the amount of movement of the stamp for a certain time interval τ, providing the necessary amount of pressing pressure P; 2) drying temperature T; 3) the final processing time $t_f . V_{n-} V_p$.

As a criterion for the efficiency of technological processes, let us take the final density ρ of the sample (or its relative compaction:

$$\overline{\rho} = \rho/\rho_0 \tag{23}$$

where ρ_o is the initial density of the impregnated wood before pressing) at a given moisture content W, i.e. $\overline{W}$ degree of required dehydration. All other indicators – compressive strength, hardness, stiffness, and other correlation ratios are related to the parameters ρ and W.

The value of ρ_o depends on the density of natural dry wood ρ_n, as well as on W_o, C and Q (Shamaev, 2003). In particular, for birch samples with ρ_d = 550-570 kg/m^3 after their impregnation in 20-30% urea solutions and the achievement of humidity W_o = 40 50%, ρ_o = 720-760 kg/m^3.

The range of changes in the end indicators ρ and W is quite wide depending on technological tasks and goals (production of sleepers, pillars, mine stand, etc.) and on average is: for the parameter ρ from 900 to 1200 kg/m^3, for W from 2 to 10%.

To achieve these parameters, the technological parameters vary in very wide intervals: the pressing speed V_n in the range from 0.2 to 20 mm/min and the corresponding pressing pressure P from 0.5 to 2.5 MPa, temperature T from 110 to 170°C, time processing t_p – from 2 to 20 hours. Such significant boundaries of the intervals determine the need to optimize these parameters in order to achieve the specified indicators for obtaining modified wood. $V_{n-} V_p$.

A model of pressing rectangular samples of wood impregnated and saturated with moisture under the action of a flat die *1* without the use of any molds is shown in Fig. 1*a*, where it is assumed that pressing a layer h of a wood sample *2* with height H and width b is carried out across the fibers in the radial (r) direction, which coincides with the direction of action of the force P with simultaneous drying in a given field.

Under the action of a compressive load P, the layer h directly under the press experiences a vertical q_v and a horizontal q_h of pressure (Shapiro et al., 2008) (Expression 4).

Calculations of the parameters of pressing and dewatering a layer of wood of size *h* during the time in the field of high temperatures *T* were carried out for the conditions of deformation across the fibers in the radial direction *r* under a flat press of heated wet birch samples impregnated with 20-30% aqueous urea solution, with the following initial data: pressing speed V_p = 1.4 (mm / min); α = 33.710-6 (1/deg), where α is the coefficient of linear expansion of wood, which characterizes the increase in the unit length of the material when heated by 1°C; W_o = 50%, ρ_o = 760 kg/m^3; *E* = 126.9 MPa; ν = 0.3, *T* = 140°C, *b* = *H* = 0.13 m, shrinkage coefficient $К_{sh}$ = 0.26, the cross-sectional area of the micro perforations is s_c = 0.00264 mm^2, the dynamic viscosity of the fluid is γ = 0.13417MPa·s.

It was established that in the process of moving the press from *h* = 0 to *h* = 1.4 mm, the linear behavior of the dependences It was established that in the process of moving the press from *h* = 0 to *h* = 1.4 mm, the linear behavior of the dependences $q_v(h)$ and $t_o(h)$ is observed, and at the time τ = 60s, the pressing pressures q_v = 1.506 MPa are achieved, which are kept constant during the optimal period, the dehydration time is t_o = 543 s. During this period, within the limits of the layer *h*, the compaction of the mass if $\bar{\rho}$ increases and its humidity *W* decreases in accordance with the data presented in Fig. 5.

The analysis of logarithmic curves indicates the existence of two sections – branches of intense and asymptotic damping of the exponents $\bar{\rho}$ and *W*, and the conjugation of these branches occurs at the moment of time *t* 3 τ = 180200s. Thus, in one pressing cycle (N_c = 1) within t_o = 543c, the relative compaction reached $\bar{\rho}$ = 1.085, the density of wood within the first layer *h* = 1.4 mm increased from 760 to 825 kg/m^3, and the humidity decreased from 50 to 49.15%.

Outside the layer *h* at some distance *r* ≥ *h*, the pressing pressure q_v causes in the wood massif the action of vertical σ_r and tangential σ_θ stresses equal to

$$\sigma_r = \frac{q_v}{(r/h)^n} \tag{24}$$

The exponent n in formula (24), as a rule, 2 is assumed to be 2 when solving the Boussinesq problem (Shapiro et al., 2008), thereby assuming that the voltages decay quite intensively with increasing distance *r*.

However, the nature of the attenuation of stresses for environments with internal friction, and these should include an array of wood, it is better to describe the coefficient *n*, equal to:

$$n = \chi - \mu, \tag{25}$$

where χ = 3 for a spherical stress front, χ = 2 for a cylindrical one, and χ = 1 for a flat one (Shemyakin, 1969; Mosinets & Abramov, 1982).

Thus, to assess the stress-strain state of an array of wood under the action of a flat stamp, we take *n* = 1-μ. In particular, for ν = 0.3 and μ = 0.43, the value of *n* = 0.57, i.e. the attenuation of the flat stress front in the sample material with distance from the surface of the press is rather slow.

In accordance with (24), when *n* = 1-μ, the vertical stresses σ_r acting in the wood mass outside the layer *h* in the *r* direction are estimated as the relative distance $\bar{r} = r/h$ from 1 to 4 varies, the attenuation pattern of which is shown in Fig. 6.

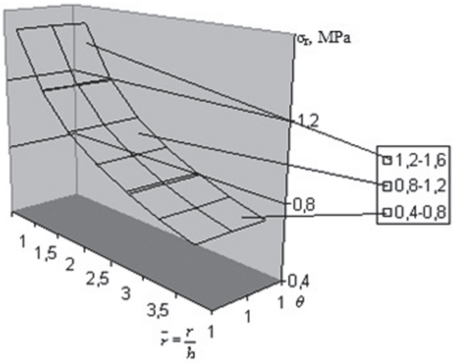

Fig. 6. Attenuation of vertical stresses in a solid wood

As follows from Fig. 6, the compressive stresses, even at a distance of the die $\bar{r}$ = 4 pips, are very significant ($\sigma_r \approx 0.7$ MPa) and will make a significant contribution to the process of pressing and dewatering wood.

Modeling of the process of pressing and dewatering wood in the field of high temperatures has shown that to ensure optimal conditions for the process of deforming the wood, it is necessary that the speed of pressing corresponds to the temperature level.

In Fig. 7 shows the dependence V_n on *T*, which indicates a non-linear increase in the speed of pressing with an in-

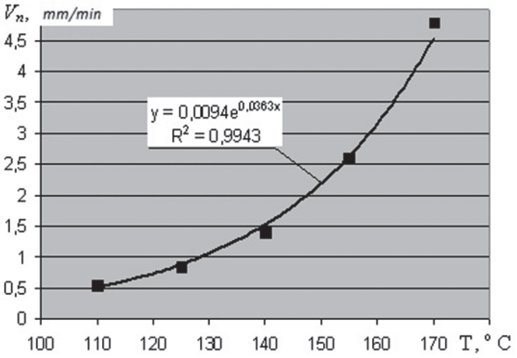

Fig. 7. Dependence $V_n(T)$ for impregnated birch samples $V_{n-}V_p$

crease in the heat treatment temperature of the sample, and the most intensive growth is observed when the level of heat treatment is reached T ≥ 140°C. $V_{n-}V_p$.

On the second cycle of processing a wood sample (N_c = 2), maintaining the pressing pressure constant and equal to q_v = 1.506 MPa, the mathematical model reproduces all the above operations and calculations, however, the fact that within the next layer *h* the array was previously subjected to general deformations ε is taken into account from the action of compressive stresses σ_r, which had an additional impact on the process of pressing and dehydration.

In Fig. 8 shows the dependence of the strain ε on σ_r.

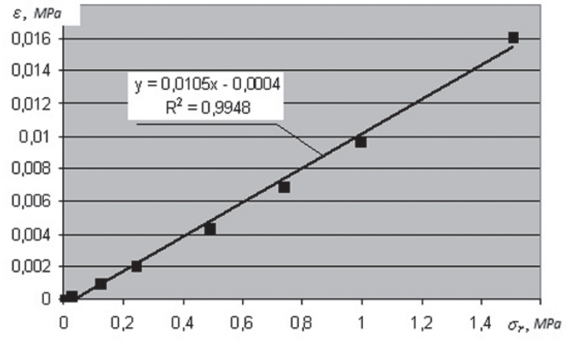

Fig. 8. The dependence of the total deformation of wood from the existing compressive stresses

Based on the data obtained in the study of the stress-strain state of the array within the next layer *h* for the initial data: $\overline{r} = 2$, q_v = 1.506 MPa and μ = 0.43 using formula (22), we obtain the value of compressive stresses σ_r = 1.015 MPa, which upon completion the first cycle (N_c = 1) determine the effect of additional common deformations of the array element Δε = 0.0103 and its corresponding additional sealing $\Delta\overline{\rho} = \Delta\varepsilon + 1 = 1.01$.

Thus, the total value of the relative compaction of the second layer will be $\overline{\rho} = 1.085 + \Delta\varepsilon = 1.095$.

Studies of pressing the array in subsequent cycles allowed us to establish the linear character of the behavior of the function $\overline{\rho}$ (N_c) shown in Fig. 9a:

$$\overline{\rho} = 1.075 + 0.01N_c \tag{26}$$

Similarly, studies on the decrease in humidity W of the next layer of the array with increasing number of cycles $N_ц$ pressing and dehydration (Fig. 9b) allowed us to obtain the dependence:

$$W = 50 - 1.0224N_c \tag{27}$$

In particular, with (27) established as *W* = 10%, N_c is 39, which corresponds to the sample processing time $t_к = N_c t_о$ = 39543/3600 = 5.9 hours, after which with (26) we estimate mass consolidation achieved $\overline{\rho}$ = 1.465 or its final density ρ = 1113 kg/m^3.

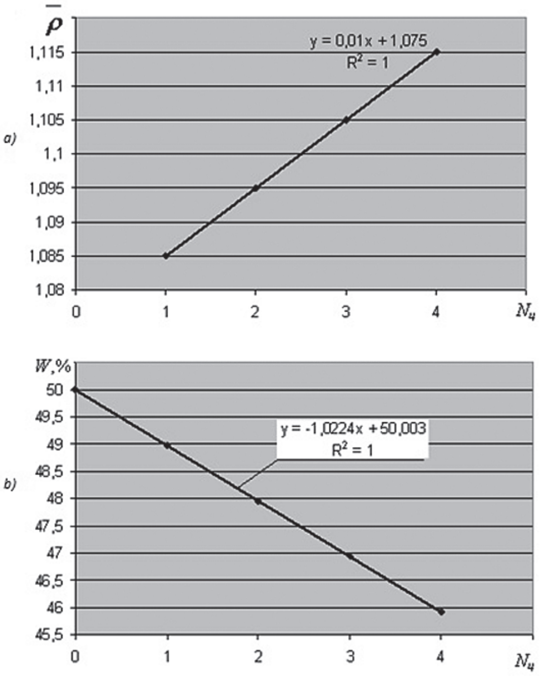

Fig. 9. The dependence of compaction of the array and its humidity on the number of pressing and dewatering cycles

If necessary, provide lower values of humidity, for example, *W* = 5%, ratios (26) and (27) give the following calculated parameters: N_c = 44, t_c = 6.6 hours, = 1.515 or $\overline{\rho}$ = 1152 kg/m^3.

Thus, the requirement to reduce the final moisture content of the sample by two times (from 10 to 5%), other things being equal and very close (less than 3.5%), its compaction results in a slight increase in processing time (by 11.5–12%).

This conclusion generally corresponds to the recommendations (Grigorev et al., 2019), where the scope of application of a modified birch-based destam (urea-plasticized wood) sample determines a wide range of changes in the final density ρ = 800-1200 kg/m^3 with an extremely narrow range of changes in the final humidity W = 4.8-5%.

As the simulation results showed, the factor of temperature of heat treatment of wood, taking into account the interrelation of parameters *T* and V_n has a significant impact on the values of $t_о$ and N_c. The revealed regularities of the pressing and dehydration processes, as well as the obtained correlation ratios with rather high values of the coefficient of determination ($R^2 \geq 0.9$), made it possible to calculate the final technological parameters with variations in humidity W, compaction $\overline{\rho}$ and temperature $T.V_{n-}V_p$

Statistical processing of the data allowed us to establish the linear multiple regression equations:

$$tk(\overline{\rho}, W, T) = (k_1W + k_2\overline{\rho})(k_3T + k_4) \tag{28}$$

And compaction:

$$\overline{\rho} = k_5T + k_6W + k_7. \tag{29}$$

To determine the conditional extremum of the function (28) along the surface of the bond (29), we searched for the extremum of the Lagrange function

$$\mathrm{L}(\overline{\rho}, W, T, \lambda) = (k_1W + k_2\overline{\rho})(k_3T + k_4) - \lambda(k_5T + k_6W + k_7) \tag{30}$$

where λ is the Lagrange multiplier.

As applied to the accepted conditions for calculating the value of the coefficients k_i, the composition is $k_1 = -0.561$; $k_2 = 7.98$; $k_3 = -0.0186$; $k_4 = 3{,}607$; $k_5 = 0.0032$; $k_6 = 0.0135$; $k_7 = 0.882$.

Given the objective function $t_c \rightarrow \min$, the following solution of the system of equations is reached:

$$\begin{aligned}
&\frac{\partial L}{\partial \rho} = k_2(k_3T + k_4) - \lambda = 0 \\
&\frac{\partial L}{\partial W} = k_1(k_3T + k_4) - \lambda k_6 = 0 \\
&\frac{\partial L}{\partial T} = \lambda k_5 + k_3(k_1W + k_2\overline{\rho}) = 0 \\
&\frac{\partial L}{\partial \lambda} = k_5T + k_6W + k_7 - \overline{\rho} = 0
\end{aligned} \tag{31}$$

With technological limitations:

$$1.2 \leq \overline{\rho} \leq 1.8;\ 2 \leq W \leq 12;\ 110 \leq T \leq 170 \tag{32}$$

As a result, it was established that the point of conditional extremum of function (28), in particular for the calculated coefficients k_i, is the $\mathrm{M_o}$ point (1.561; 10; 170), and the required and sufficient sample processing time was $t_c = 3.7$ hours. When this is achieved, the density of wood $\rho = 1186$ kg/m^3 and its humidity $W = 10\%$. For comparison and analysis of the results obtained, we turn to the technology for producing thermoplastic wood, where as a result of preliminary dehydration of blanks up to 40%, their warming up to 132°C (urea to biuret transition temperature) and heat treatment at $T = 170$°C, pressing under pressure $q_v = 2.5$ MPa for 2 hours provided a decrease in humidity to 8–12% and density to 1200 kg/m^3.

Thus, the developed mathematical model allows at the stage of preliminary theoretical estimates to determine the optimal parameters of the process of compaction of impregnated wood in the process of its pressing, dewatering and drying.

Conclusions

The regularities of the change in time of the flow rate of the fluid in the process of pressing samples are established and it is shown that the period of intensive decline of this indicator is 58-85% (average 70-72%) of the period of its asymptotic decline. The nonlinear nature of the growth rate of the sample was revealed as the temperature of its heat treatment increased, with the most intense growth rate being observed when the temperature level exceeded 140°C. The degree of influence of the number of pressing cycles on the development of the process of compaction of plasticized wood in the process of its dehydration is shown. Thus, with a given final moisture content of wood equal to 10%, the required number of pressing cycles reaches 39, which corresponds to the sample processing time of 5.9 hours and achieve a degree of compaction of 46.5%. As a result of the implementation of the developed mathematical model, an equation of linear multiple regression is obtained depending on the sample processing time on the required values of their compaction and humidity in a given temperature field, which forms a reliable theoretical basis for solving various optimization problems of the technological parameters of the pressing and dewatering plasticized wood samples.

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