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THE EFFECT OF TEMPERATURE AND MOISTURE CHANGES ON MODULUS OF ELASTICITY AND MODULUS OF RUPTURE OF PARTICLEBOARD

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ABSTRACT

Taking into account nonlinear effects in the reaction of wood composite materials during the thermal, moisture and power loads, the strength phenomenological model can be created. Bending strength and modulus of elasticity of different types of particleboards were studied at the temperatures of 20, 40, 60, 80 and 100 °C and moisture content of 6, 8, 9, 11 and 15 % using the standard tensile testing machine. Based on the results of the tests, permanent members of the phenomenological model were determined describing adequately the strength and rigidity of particleboard.

Key words: non-linear effects, bending strength, modulus of elasticity in bending, strength phenomenological model

INTRODUCTION

In order to utilize the full potential of wood composite materials (WCM), such as particleboard (PB) as building material, the changes of mechanical properties during exposure to different temperature and relative humidity must be known (AYRILMIS *et al*. 2010, BEKHTA and MARUTZKY 2007, BEKHTA and NIEMZ 2009). For reasons of safety, it is especially important to know the strengths of load bearing WCM structures under thermal, humidity and power conditions (DEXIN and ÖSTMAN 1983, SUZUKI and SAITO 1987, KULMAN *et al*. 2015). However, analytical methods are unavailable which would predict the performance of load structural WCM members during loads, yet. Therefore, the objective of this investigation is to develop a model which can be used to predict changes in the tensile and compressive properties of WCM during changes temperature and moisture content (MC) exposure.

Usually the strength calculations are carried out according to Hooke's law, which assumes a linear dependence of stresses and deformations. In the classical approach to the problem of strength accepted that failure occurs when a certain combination, which includes stress, strain, temperature, and some other parameters (describing the state of the material and its specific properties) reaches a critical value (PANASIUK 1988). It is considered that in the space of all possible values of these parameters there is a closed surface is described by the relation:

$$\varphi = F(\sigma, \varepsilon, T, W, C_n) \tag{1}$$

where C_n – parameters characterizing the properties of the macro real body volume determined experimentally. This limits the scope of permissible surface, in terms of strength, the material states.

The specific form of the phenomenological relation (1) for each material is established based on accepted postulates (hypotheses) about the destruction and the necessary experimental research on setting environments C_n. However, the generally accepted equations of limit states, which would explicitly take into account the effect of time, temperature, humidity, and the load is not created.

Since WCM for different thermal, moisture, power conditions will be in different states, tensile strength and modulus of elasticity (MOE) will differ its deviation from the ideal state in conditions in which the material has a maximum strength and stiffness. The phenomenological equation of state of the material can be expressed in the general form:

$$\sigma_{T,W,t} = f(\sigma_0, T, W, t) \tag{2}$$

$$E_{T,W,t} = f(E_0, T, W, t) \tag{3}$$

where $\sigma_{T,W,t}$ – limit strength in its various states; σ_0, E_0 – the maximum possible value of the tensile strength and elastic modulus of the material under ideal conditions, i.e. in the absence of external influences, MPa; T – thermostat temperature (ambient) K; W – moisture content, %; t – time, s.

In this paper, the equation of state without taking into account the time factor and scale factors is proposed in the form of an autonomous system. Then, at t = 0 the equation of state describes the short-term strength for the short quasi-static loading at a given temperature - humidity conditions. When $t \gg 0$ equation (2), (3) will be described by equations of state under long-term loading, i.e. the long-term strength.

Phenomenological model builds on the behaviour of the object as the result of a process, the essence of which is generally understood approximately, but details are not yet clear. In the model introduced some "constants", describing the specific behaviour of the object, with specification of the object, but without specifying the exact meaning of these “permanents” (Prigogine and Kondepudi 1999).

The aim of this study is to develop a phenomenological model of strength and stiffness for composite materials based on wood under the influence of thermo – moisture – power loads, which takes into account the non–linear nature of the reaction this material to the external influences.

MATERIAL AND METHODS

Three types of particleboard bonded with urea-formaldehyde resin commercially produced by Kronospan UA Ltd. were used in this study: melamine faced particleboard (MF PB), oak veneered particle board (VF PB) and particleboard P2 (P2 PB) according to EN 312 type P2. Test pieces with the thickness of 18 × 450 × 50 mm were cut from each type of board. Before testing, pieces were conditioned at 20 °C and 65% RH. The average densities of specimens were 757 kg/m^3, 792 kg/m^3, 733 kg/m^3 and moisture content 5%.

Static 3-point bending tests were carried out in the universal test machine with temperature-controlled chamber at the speed deformation 2 mm/min. Investigated temperatures were 20 °C, 40 °C, 60 °C, 80 °C and 100 °C. Investigated moisture contents were 6 %, 8 %, 9%, 11% and 15 %.

Methods for determining the ultimate strength and modulus of elasticity in bending are described in detail in a previous paper (Kulman *et al*. 2017). However, the methodology for constructing phenomenological models of strength and rigidity was fundamentally different (KULMAN 2017).

As during model building considering the strength, only elastic deformation, the tensile strength and modulus of elasticity in the elastic deformation depends linearly on the external thermo – moisture – power of influence. Therefore, the rate of destruction in this area can be assumed as constant, and the process of maintaining strength (loss of strength), is considered analogous reaction of zero order. The elastic deformation order of reaction does not change. The statement that the order "of the reaction strength loss" does not change based on the curve also the "force – displacement" analysis when tests using a standard tensile strength machine. Character of the curve changes slightly for different temperatures (KULMAN *et al*. 2015). In addition, a kinetic measurement is to determine the long-term strength of particleboard (BOIKO *et al*. 2013) talking about the fact that the order of reaction process of losing long–term strength also does not change. And while there is the temperature dependence of the speed of this process following the simplest form, the Arrhenius equation (STILLER 1989):

$$k\ (T) = Ae^{\frac{-E_A}{RT}} = Ae^{\frac{-T_A}{T}} = Ae^{T_e} \tag{4}$$

where: A, E_A – independent constants (or nearly independent) in the temperature range studied; E_A – observed (imaginary) activation energy, kJ/mol; R = 0.0083 kJ/mol*K – universal gas constant; $T_A = E_A / R$ – activation temperature, K.

In this case, the activation temperature is equal to the upper temperature limit at which the body has the properties to withstand an external load, that is, the sublimation temperature $T_A \propto T_m$; $T_e = T / T_m$ – efficient temperature, which characterizes the deviation of the current temperature of the test by limiting the activation temperature in the range of operating temperatures $T \in T_{\min}...T_{\max}$. A – pre-exponential factor, which is postulated on the basis of the purpose for which is compiled by the Arrhenius equation. Its value can be determined based on conducted tests. In our case, this is the maximum possible strength of the material in the case of the minimum temperature, that is, when $T_{\min}$ = 0 °K.

Arrhenius equation shows that at constant temperature, constant speed *k(T)* of a process is determined by the activation energy. The higher the numerical value of the activation energy E_A, the less active molecules (intermolecular bonds), the smaller the number of effective unbroken bonds and the thus lower the rate constant and the strength loss rate itself. The higher activation energy, the more difficult to break the bonds between the molecules and the higher strength. In modern interpretation, Arrhenius equation determines not only the temperature dependence of the process rate k, for example, the chemical reaction rate, but the rate of diffusion, longevity, relaxation period, the option of destruction. Thus in each case the value included in this equation have a different interpretation (STILLER 1989). Most important constant of integration A, (pre-exponential factor) is interpreted as a constant at the threshold included in the equation of variables that determine the nature of external influence (temperature, load, humidity, etc.). Moreover, A and E_A – constants, independent (or nearly independent) in the investigated temperature range.

Taking all the above mentioned assumptions can be argued that the experimentally observed dependence should tensile strength and modulus of temperature in the form of the Arrhenius equation:

$$\sigma_{W,T} = \sigma_0 e^{\alpha T_e}, \tag{5}$$

where $\sigma_{W,T}$ – actual, current strength, the strength at the current moisture content *W (%)* and temperature *T (°K)*; σ_0 – constant equal to the maximum for the material tensile strength at *W = 0,%* and *T = 0,°K;* α – constant coefficient, which characterizes the degree of influence of temperature taking into account other factors, and their interaction. In the case of recording only one factor influence, temperature: $\alpha\big|_{W=0\%} = 1$.

By analogy with the effect of temperature on the strength postulate influence of humidity on the strength of typing in the equation (2), (3) efficient moisture W_e. In addition, the construction of the model will take into account its non-linearity, entering into the equation the factor of interaction between effective temperature and moisture, in the form of their multiplication T_eW_e (KULMAN 2011, KULMAN and BOIKO 2016). The equation describing the phenomenological nonlinear model of strength and stiffness in the form of the Arrhenius equation takes the form:

$$\sigma_{W,T} = \sigma_0 e^{\alpha T_e} e^{\beta W_e} e^{\gamma W_e / T_e} \tag{6}$$

$$E_{W,T} = E_0 e^{\delta T_e} e^{\varepsilon W_e} e^{\theta W_e / T_e} \tag{7}$$

where: $\sigma_{W,T}$ – actual, current strength, that strength at the current moisture content *W (%)* and temperature *T (°K)*; $W_e = (W_m - W)/W_m$ – effective moisture;
W_m – maximum permissible moisture content of the material in which it has sufficient elastic properties for use, %; *W* - current moisture during operation, %;
$T_e = (T_m - T)/T_m$ – effective temperature;
T_m – temperature limit being material to take external loads sufficient for its operation, °*K*;
T – current temperature material during its operation, °*K*;
α, β, γ, δ, ε, θ – constant coefficients;
α, δ – take into account the effect of temperature on the material tensile strength and modulus of elasticity;
β, ε – take into account the effect of moisture content on the tensile strength and modulus of elasticity;
γ, θ – the change in strength properties of the material in the joint action of humidity and temperature is not linear process of changing strength;
$E_{W,T}$ – current modulus of elasticity, *MPa*;
E_0 – constant factor equal to the theoretically maximum possible for the material modulus of elasticity at *W = 0,%* ;
T = 0, °K.

Moreover, the values of σ_0, E_0, *α, β, γ, δ, ε, θ* are determined by solving the system of equations: $W_e = (W_m - W)/W_m$

$$\begin{cases} \ln \sigma_{W_1T_1} = \ln \sigma_0 + \alpha W_{e1} + \beta T_{e1} + \gamma \dfrac{W_{e1}}{T_{e1}} \\ \ln \sigma_{W_2T_2} = \ln \sigma_0 + \alpha W_{e2} + \beta T_{e2} + \gamma \dfrac{W_{e2}}{T_{e2}} \\ \ln \sigma_{W_3T_3} = \ln \sigma_0 + \alpha W_{e3} + \beta T_{e3} + \gamma \dfrac{W_{e3}}{T_{e3}} \\ \ln \sigma_{W_4T_4} = \ln \sigma_0 + \alpha W_{e4} + \beta T_{e4} + \gamma \dfrac{W_{e4}}{T_{e4}} \end{cases} \tag{8}$$

$$
\begin{cases}
\ln E_{W_1T_1} = \ln E_0 + \delta W_{e1} + \varepsilon T_{e1} + \theta \dfrac{W_{e1}}{T_{e1}} \\
\ln E_{W_2T_2} = \ln E_0 + \delta W_{e2} + \varepsilon T_{e2} + \theta \dfrac{W_{e2}}{T_{e2}} \\
\ln E_{W_3T_3} = \ln E_0 + \delta W_{e3} + \varepsilon T_{e3} + \theta \dfrac{W_{e3}}{T_{e3}} \\
\ln E_{W_4T_4} = \ln E_0 + \dfrac{\delta}{W_{e4}} + \varepsilon T_{e4} + \theta \dfrac{W_{e4}}{T_{e4}}
\end{cases}
\tag{9}
$$

where T_{e1}, T_{e2}, T_{e3}, T_{e4} – effective temperature series of four tests, °*K*; W_{e1}, W_{e2}, W_{e3}, W_{e4}, – effective material moisture during the four-test series, *%; σ_{W1T1}, σ_{W2T2}, σ_{W3T3}, σ_{W4T4}* – modulus of rupture at the appropriate temperature and MC, *MPa*; E_{W1T1}, E_{W2T2}, E_{W3T3}, E_{W4T4} – modulus of elasticity at the appropriate temperature and MC, *MPa*.

RESULTS AND DISCUSSION

The experimental factor levels and test results are shown in Table 1. For example summarized ruptures envelope for load-displacement curves in coordinates stress-rupture time for MF PB under different conditions shown in Fig.1. In all cases of tests carried out with increasing temperature and humidity, the strength and modulus of elasticity of the material decreased while increasing the time to failure.

Tab. 1 Experimental factors levels and test results for particleboards.

Board type	Test group number	Test conditions		Test results	
		Temperature (°C)	Moisture content (%)	bending strength (MPa)	modulus of elasticity in bending (MPa)
MF PB	1	20	6	16.80 ± 1.17[a]	1866.5 ± 95[a]
	2	40	8	15.55 ± 0.93	1727.6 ± 88
	3	60	9	13.80 ± 0.62	1533.2 ± 74
	4	80	11	11.30 ± 0.15	1255.4 ± 36
	5	100	15	8.00 ± 0.12	922.1 ± 22
VF PB	1	20	6	19.68 ± 0.55	2582.0 ± 112
	2	40	8	19.00 ± 0.49	2492.8 ± 95
	3	60	9	17.50 ± 0.38	2296.0 ± 86
	4	80	11	15.30 ± 0.33	2007.4 ± 78
	5	100	15	12.00 ± 0.35	1674.4 ± 60
P2 PB	1	20	6	14.80 ± 0.44	1571.9 ± 65
	2	40	8	13.40 ± 0.33	1423.2 ± 56
	3	60	9	11.70 ± 0.21	1242.7 ± 48
	4	80	11	9.50 ± 0.15	1009.0 ± 33
	5	100	15	7.50 ± 0.11	755.3 ± 23

[a] The confidence interval is indicated at p = 0.05 level.

For each species, analysis of variance (ANOVA) was conducted to study the effect of temperature and MC on the MOR and MOE at a 0.05 significance level. Results of ANOVA and multiple comparison statistical analysis for temperature and moisture content are shown in Table 2.

The significance value for MOR and MOE between 20 °C and 100 °C, and for moisture content between 6% and 15%, were less than 0.05, indicating that the effect of different temperatures on MOR and MOE for this pairs are statistically significant. The ANOVA results showed that the temperature had a more significant effect than MC on the MOR of MF PB, but MC had a more significant effect than temperature on the MOE.

Tab. 2 ANOVA for bending strength and modulus of elasticity in bending for particleboards.

Dependent variable for board type	Source	*SS* [a]	*df* [b]	*MS* [c]	*F* ratio	*p* value
Bending strength, MF PB	Moisture content	9.135	4	2.2839	142.41	0.000
	Temperature	153.686	4	38.4216	2395.73	0.000
	Error	0.257	16	0.016		
	Total	163.078	24			
Modulus of elasticity in bending, MF PB	Moisture content	49612.5	4	12403.1	19.99	0.000
	Temperature	2864606	4	716151.5	1096.49	0.000
	Error	10450	16	653.125		
	Total	2924668.5	24			
Bending strength, VF PB	Moisture content	2.205	4	0.55	96.92	0.000
	Temperature	194.3	4	48.58	8540.7	0.000
	Error	0.1	16	0.006		
	Total	196.6	24			
Modulus of elasticity in bending, VF PB	Moisture content	92820	4	23220	99.28	0.000
	Temperature	2768343	4	692086	2959	0.000
	Error	3742	16	2339		
	Total	2864966	24			
Bending strength, P2 PB	Moisture content	0.77	4	0.19	16.7	0.000
	Temperature	1723	4	431	3742.4	0.000
	Error	0.184	16	0.0115		
	Total	1733	24			
Modulus of elasticity in bending, P2 PB	Moisture content	23312	4	6328	34.9	0.000
	Temperature	2120947	4	530236	2930	0.000
	Error	2895	16	180.9		
	Total	2149154	24			

[a] *SS* – sum of squares
[b] *df* – degree of freedom
[c] *MS* – mean square

Based on the data obtained in the experiments, the constants in phenomenological models of MOR (6) and MOE (7) for each particleboard type were calculated using the system of equations (8) and (9). The results of calculations are presented in Tab. 3.

Tab. 3 Results of calculating the constants in phenomenological models of strength (MOR) and stiffness (MOE) for each particleboard types.

Board type	Constants in model of MOR				Constants in model of MOE			
	σ_0 *(MPa)*	α	β	γ	E_0 *(MPa)*	ε	δ	θ
MF PB	90.92	–14.13	9.23	–1.56	15675	–15.45	9.91	–1.81
VF PB	126.27	–10.30	6.58	–1.43	21605	–13.10	8.02	–1.55
P2 PB	171.15	–15.55	10.11	–2.03	9238	–13.45	9.03	–1.68

Using parameter is found strength using formulas (6), (7) calculate that a bootie design tensile strength and elastic modulus parts running on pure driving together when the temperature operating range from 20 to 100 °C and moisture content from 6% to 15%.

Fig. 1, 2 and 3 shows the results of calculations of strength and modulus of rupture depending on the temperature – moisture conditions for three types of particleboards.

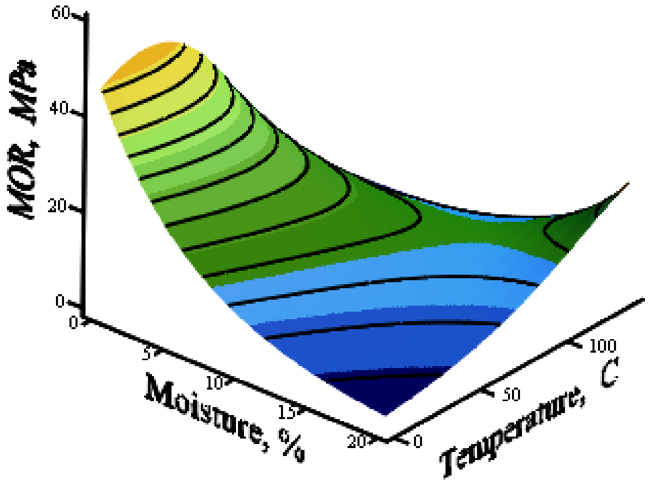

Fig. 1 Changes mean bending strength (MPa) melamine faced particleboard depends from temperature (°C) and MC (%)

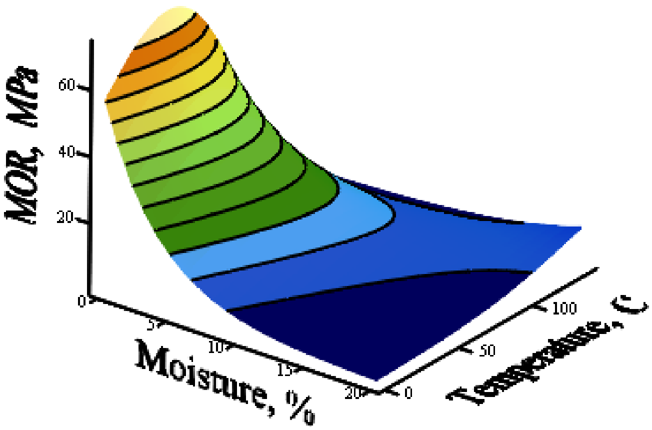

Fig. 2 Changes mean bending strength (MPa) veneered faced particleboard depends from temperature (°C) and MC (%)

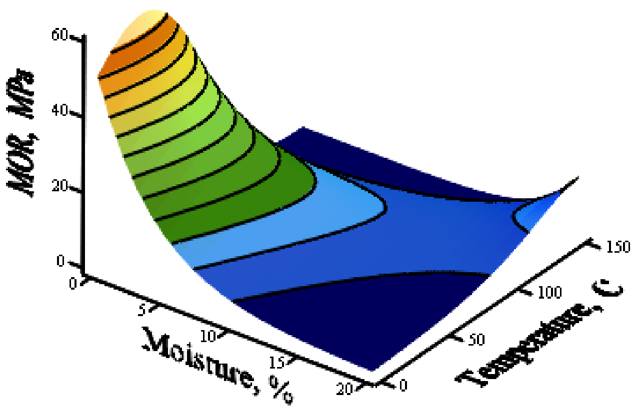

Fig. 3 Changes mean bending strength (MPa) particleboard (P2 PB) depends from temperature (°C) and MC (%)

Fig. 4, 5 and 6 show the results of calculations of stiffness like as modulus of elasticity in bending depending on the temperature – moisture conditions for three types of particleboards.

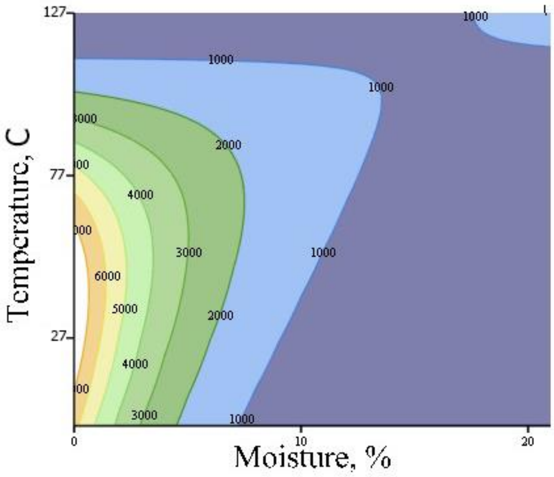

Fig. 4. Changes mean modulus of elasticity in bending (MPa) melamine faced particleboards depends from temperature (°C) and MC (%)

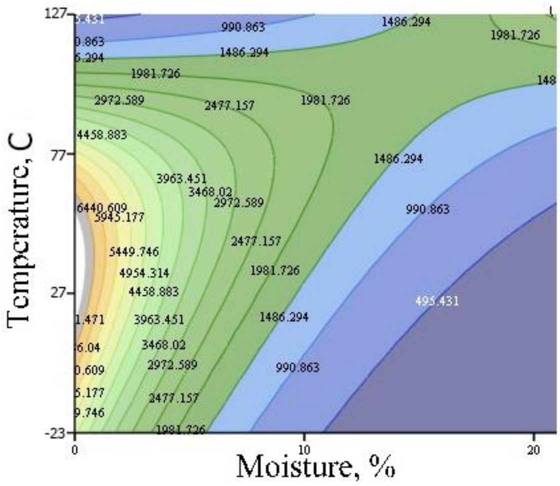

Fig. 5. Changes mean modulus of elasticity in bending (MPa) veneered faced particleboard depends from temperature (°C) and MC (%)

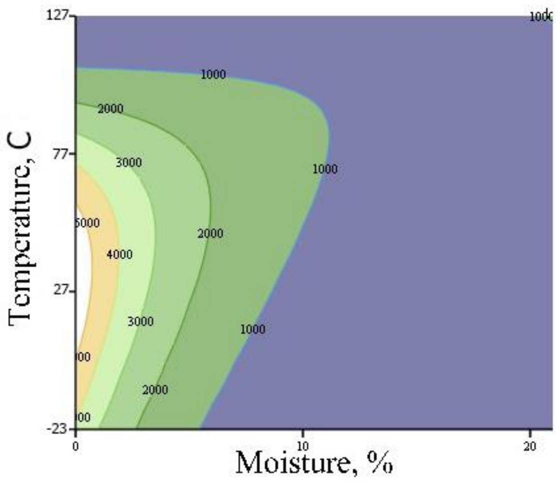

Fig. 6. Changes mean modulus of elasticity in bending (MPa) of particleboard type P2 depends from temperature (°C) and MC (%)

Phenomenological model of strength (MOR) and stiffness (MOE) presented in Fig. 1 to 6 graphically limited in the variables coordinates a surface of the second order, the ultimate surface of strength and stiffness. Geometrically, it is the hyperbolic paraboloid. It is formed by the non-linear terms in the equations (6), (7). It characterizes the interaction of temperature and moisture on the strength and stiffness properties of the material.

Taking into account nonlinear effects in the reaction of wood composite materials during the thermal, humidity and power loads allows offering strength phenomenological model. Using the model to predict the tensile strength and modulus of elasticity wood composite materials for the specific thermo – moisture – power conditions of its use.

Based on the results of the tests, permanent members of the phenomenological model were determined that adequately describes the strength and stiffness of particleboards.

CONCLUSION

The first created phenomenological models of strength (MOR) and stiffness (MOE) of particleboard graphically coordinate the surface of the boundary strength and stiffness in the form of a hyperbolic paraboloid that is formed by nonlinear terms in the model equations and characterizes the interaction of temperature and humidity with the strength properties of the material. Taking into account non-linear effects in the reaction of wood composite materials under thermal, humidity and power loads, it is possible to propose phenomenological strength models and apply them to predict the ultimate strength and modulus of elasticity of particleboard for specific operating conditions. Based on the test results, the permanent members of the phenomenological model were determined, which adequately describe the strength and rigidity of the particleboard when changing external influences in a wide range. The created method allows to significantly reduce the time required for testing and determine the strength parameters of the material when changing the thermo–moisture–strength loads and makes it possible to estimate the preservation of the strength properties of new materials and to predict the strength in the work of the structures already created.

REFERENCES

AYRILMIS, N., UMIT, B., NUSRET, A.S. 2010. Bending strength and modulus of elasticity of wood-based panels at cold and moderate temperatures. In Cold. Reg. Sci. Technol., 63: 40–43.

BEKHTA, P., MARUTZKY, R. 2007. Bending strength and modulus of elasticity of particleboards at various temperatures. In Holz Roh-Werkst., 65: 163–165.

BEKHTA, P., NIEMZ, P. 2009. Effect of relative humidity on some physical and mechanical properties of different types of fiberboard. In Eur. J. Wood Prod., 67: 339–349.

BOIKO, L.M., GRABAR, I.G., KULMAN, S.M. 2013. Durability particleboards in furniture. Osvita Ukrainy, Ukraine, 2013, 210 p.

DEXIN, Y., ÖSTMAN, B.A.L. 1983. Tensile strength properties of particle boards at different temperatures and moisture contents. In Holz Roh-Werkst., 41(7): 281–286.

KULMAN, S. 2011. Nonlinear effects caused deformation and fracture composite materials based on wood. http://elibrary.nubip.edu.ua/13490/1/11ksm.pdf.

KULMAN, S., BOIKO L., ANTSYFEROVA A. 2015. Bending strength (modulus of rupture) and modulus of elasticity of MDF different density at various temperature. Annals of Warsaw University of Life Sciences - SGGW Forestry and Wood Technology 91: 101–106.

KULMAN, S., BOIKO, L. 2016. Non-linear effects in the reaction of wood composite materials during the thermal, humidity and power loads. Annals of Warsaw University of Life Sciences - SGGW Forestry and Wood Technology 95: 159‒165.
KULMAN, S. 2017. Method for predicting the bending ultimate strength (MOR) and modulus of elasticity in bending (MOE) composite materials based on wood. Patent 114560 – UA, 2017.
KULMAN, S., BOIKO, L., PINCHEVSKA O., SEDLIAČIK J. 2017. Durability of wood-based panels predicted using bending strength results from accelerated treatments. In Acta Facultatis Xylologiae Zvolen, 59(2): 41‒52.
PANASIUK, B. 1988. Fracture mechanics and strength of materials: Handbook: Volume 1. Kiev Sciences Dumka. Kiev, Ukraine, 1988, 451 p.
PRIGOGINE, I., KONDEPUDI, D. 1999 Modern Thermodynamics. From Heat Engines to Dissipative structures. Edition Odil Jacob, NY, 1999, 652 p.
STILLER, W. 1989. Arrhenius Equation and Non-Equlibrium Kinetics. 100 Years Arrenius Equation. BSB B. G. Teubener Verlagsgesellschaft, Leipzig, 1989, 354 p.
SUZUKI, S., SAITO, F.1987. Effects of environmental factors on the properties of particleboard. I. Effect of temperature on bending properties. In Mokuzai Gakkaishi, 33(4): 298‒303.

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