ACTA FACULTATIS XYLOLOGIAE ZVOLEN, 59(2): 41−52, 2017
Zvolen, Technická univerzita vo Zvolene
DOI: 10.17423/afx.2017.59.2.04

DURABILITY OF WOOD-BASED PANELS PREDICTED USING BENDING STRENGTH RESULTS FROM ACCELERATED TREATMENTS

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ABSTRACT

The development of new particleboard requires an objective evaluation of their strength and operational properties. As a rule, these materials are tested for strength (MOR) and stiffness (MOE), since these tests can be carried out quickly. Subsequently, tests for long-term strength (creep) and durability are following. Tests for long-term strength and durability are time consuming and laborious, therefore new accelerated test methods are constantly required. The method of predicting is based on the kinetic concept of the strength of solids. This technique connects the time destruction of the test piece with its moisture content under the influence of external thermal and force loads. The data given in this work allow to develop a mathematical model describing the change in the long-term strength of composite materials on wood fillers, and to evaluate the influence of external factors on the strength characteristics of the composite during the manufacturing and operation process.

Key words: wood-based panel, predicting durability, durability performance, accelerated aging treatments.

INTRODUCTION

Mat-formed wood-based panels, such as particleboards (PB) and medium-density fibreboards (MDF), have become widely used in residential construction in recent years. For such use, long-term durability of the wood-based panels is important. Estimating how long panels maintain the required performance under actual environmental conditions has been a goal of studies evaluating the durability of wood-based materials. To achieve this, the deterioration mechanism(s) must be clarified in relation to various conditions.

The non-structural application of wood-based panels such as particleboards for furniture has considerably increased in the last few years, because of their favourable physical and mechanical properties, ease of machining, availability, and cost-effectiveness.

Several researchers have reported on the effects of temperature on the mechanical properties of wood (Gerhards 1982, Lenth and Kamke 2001, Young and Clancy 2001, Bekhta and Niemz 2003, Moraes *et al.* 2005; Green and Evans 2008a,b, Kocaefe *et al.* 2008, Ayrilmis *et al.* 2009, Manriquez and Moraes 2010). They observed that the strength of lumber decreases as the temperature increases. There are some publications on the effect of temperature on mechanical properties of oriented strand boards (OSB), and plywood from the viewpoint of the structural application considering the change of the service environment and fire resistance (Back and Sandstrom 1982, Yu and Ostman

1983, SUZUKI and SAITO 1987, BEKHTA *et al.* 2003, SONDEREGGER and NIEMZ 2006, BEKHTA and MARUTZKY 2007, AYRILMIS *et al.* 2010, SINHA *et al.* 2011).

In many situations where the boards are subjected to load for considerable long periods and various relative humidity (RH) of surrounding atmosphere, they show a notable deformation resulting from an interaction between applied stress and moisture content (MC) change (ARMSTRONG and GROSSMAN 1972, HALLIGAN and SCHNIEWIND 1972). Rheological equations quantifying the deformation of wood-based materials under combinations of mechanical stress and moisture change have been proposed (LEICESTER 1971, RANTA-MAUNUS 1975). The total deformation of wood composite panels under rapid MC change and short-term loading conditions consists mainly of initial deformation and MS deformation.

Mechanical durability of wood-based panels is usually evaluated by laboratory-accelerated aging tests such as simple hot water soaking, boiling, steaming, freezing, drying and their combinations. However, relationships between these treatments and actual service environments are still in question. To answer this, researchers have reported some attempts to correlate degradation caused by outdoor aging with that by laboratory accelerated aging (HANN *et al.* 1962, RIVER 1994, OKKONEN and RIVER 1996). Although correlating these results can justify a method of laboratory-accelerated aging tests, it is still uncertain how durable wood-based panels are in actual services, especially in countries with humid and high temperature seasons.

Methods for evaluating the durability of wood-based panels include long-term and short-term tests. Long-term evaluation, such as outdoor exposure tests, is a method to evaluate long time frames by incorporating the factor of elapsed time. However, outdoor exposure tests have many disadvantages, such as being time-consuming and difficult to carry out on; moreover, these tests are influenced by differences caused by the test location. In contrast, short-term evaluations assess changes in mechanical properties after accelerated aging treatments, such as water immersion, boiling, steaming, freezing, or drying. Accelerated aging tests are superior to short-term outdoor exposure tests, and they are essential in determining the durability of wood-based panels.

Such accelerated aging tests may seem artificial, but in recent decades, many attempts have been made to correlate degradation caused by outdoor aging with that induced by laboratory-accelerated aging (LEHMANN 1977, 1978) including the use of ASTM D1037, APA D-1 and D-4, and V313 tests, because the results of outdoor aging tests are sometimes used as basic indicators when determining standardized test methods (DINWOODIE 1981, OKKONEN and RIVER 1996).

The study properties of the PB are usually based on the Boltzmann Superposition Principle describing the response of a material to different loading histories (ASTM D 1037-99). The Boltzmann superposition principle states that the response of a material to a given load is independent of the response of the material to any load affecting the material. The deformation of a specimen is directly proportional to the applied stress, when all deformations are compared to equivalent times. However, the principle does not take into account the mutual influence of external factors. It is only valid in linear elastic region.

Previous studies have shown a significant dependence of the PB strength and rigidity on the temperature and moisture content of the material. In this case, phenomenological relationships were obtained in the form of formulas that relate these quantities, on the basis of which it is possible to predict the change in strength characteristics with a change in the conditions of their operation.

At the same time, when predicting the longevity of these materials on the basis of the kinetic theory strength of solids (REGEL *et al.* 1974), in the canonical formula of Zhurkov (1965), or the refined Zhurkov-Ratner formula, only the temperature is entered. An attempt to use the Zhurkov-Ratner model to composite materials based on wood revealed that the influence of moisture content was taken into account by introducing additional corrections, determined as a result of prolonged experiments (RATNER and YARTSEV 1992). However, the practical use of climate corrections has shown that their application is limited only by the range of admissible values of external factors.

The introduction of the time scale of the process of destruction led to the creation of a kinetic theory of strength. The origins of this theory relate to the work of the Ioffe Physical-Technical Institute of the Russian Academy of Sciences, which were performed in the middle of the last century. The time dependences were proposed in describing the relaxation properties for viscoelastic deformation of solids, in the form of generalized Maxwell's equations (ALEKSANDROV 1941). The fundamental form of the kinetic theory of strength is the Zhurkov equation (ZHURKOV 1965):

$$\tau = \tau_0 \exp\left[\frac{U_0 - \gamma\sigma}{RT}\right] \tag{1}$$

where τ – is the durability at temperature T and load σ; U_o and γ are parameters of the equation, which have a simple physical meaning.

The kinetic theory is based on the idea of the breakdown of the chemical bond at a thermal, Boltzmann process, which is activated by the mechanical stress σ. In this case, U_o is understood as the activation energy of the process (it must be equal to the energy of the chemical bond being broken, to the period of oscillations of chemically bound atoms (the value is on the order of $10^{-12...-13}$ s^{-1}). If σ is the stress on the molecule, $\gamma\sigma$ is mechanically induced decrease in the energy of the ruptured coupling, and γ is the coefficient of transformation of the mechanical stressing into energy, then τ is the expectation time for the decay of the molecule, that is, the waiting time for the energy fluctuation $E_f = (U_o - \gamma_\sigma)$ for the given bond.

Into the formula (1), fourth parameter for polymeric materials was physically induced, after which, it is acquired following (RATNER AND YARTSEV 1992):

$$\tau = \tau_m \exp\left[\frac{U_0 - \gamma\sigma}{RT}\left(1 - \frac{T}{T_m}\right)\right], \tag{2}$$

where τ_m, U_0, γ and T_m - physical (thermoactivation) material parameters (TAP): τ_m - minimum durability (the period of oscillation of kinetic units - atoms, atom groups, segments) *s; U_0* - maximum destruction activation energy, kJ·mol; γ - structural and mechanical parameters, kJ/(mol·MPa); T_m - temperature limit existence of solids (temperature degradation), K; R - universal gas constant, kJ/(mol·K); τ - time to fracture (durability) s; σ - stress, MPa; T - temperature, °K.

Traditional methods for determining TAP in modern science of materials still use grapho-analytical methods for their determination. However, they are quite time-consuming and not accurate enough. In this regard, we proposed a more accurate, analytical way of determining TAP (BOIKO *et al.* 2013). According to this method, tests for durability are carried out according to a special plan, and the parameters are calculated analytically by the formulas:

$$\begin{aligned}
&\lg\tau_m = (\lg\tau_3(\lg\tau_2 - \lg\tau_4) - \lg\tau_4(\lg\tau_1 - \lg\tau_3))/(\lg\tau_2 - \lg\tau_4 - \lg\tau_1 + \lg\tau_3);\\
&x_1 = 1000/T_1,\quad x_2 = 1000/T_2;\ \gamma = (U_1 - U_2)/(\sigma_1 - \sigma_2);\\
&U_1 = 2{,}3R(\lg\tau_1 - \lg\tau_2)/(T_1^{-1} - T_2^{-1});\ U_2 = 2{,}3R(\lg\tau_3 - \lg\tau_4)/(T_3^{-1} - T_4^{-1});\\
&U_0 = \gamma\sigma_2 + U_2,
\end{aligned} \tag{3}$$

where τ_i, σ_i, T_i – time to fracture, stress, and heat for i – sample test.

However, since TAPs are determined by testing a long durability at constant load, the time of testing and in accordance with the complexity of a long way. At the same time, it is well known that the mechanical properties of composite materials, which include wood, largely depend on their moisture content.

The aim of this study is evaluating the durability of wood-based panels using bending strength results from accelerated treatments. The main results of the study of the longevity of lined particleboard in furniture designs are set forth in the monograph (BOIKO *et al.* 2013). The purpose of this work is to create the quick methodology for evaluating the long-term strength of wood based composite materials, taking into account the effect of external force, temperature and moisture content influences.

MATERIAL AND METHODS

Material

Three commercially-produced structural particleboard bonded with urea formaldehyde resin (UF) were provided by Kronospan UA Ltd., for this study: melamine faced particleboard (MF PB) according to EN 14322; veneered by oak particleboard (VF PB) according to EN 316, EN 622-5 and particleboard P2 (P2 PB) according to EN 312 - type P2; EN 13501-1: class D-s1, d0. For each type, two regular-size (2750 mm × 1830 mm) of boards with thicknesses of 18 mm were cut into 450 mm (length) × 50 mm (width) pieces. Before cutting, panels were stored in a conditioning room maintained at 20 °C and 65% RH.

Static 3-point bending tests were carried out in the universal test machine with temperature-controlled chamber. Specimens were prepared and cut according to ASTM D 1037-99. Loading and deflection were measured, and MOR and MOE were calculated according to Section 9 in ASTM D 1037-99. Investigated temperatures were 20 °C, 40 °C, 60 °C, and 80 °C. Investigated moisture content (MC) were 6 %, 8 %, 9%, 11% and 15 %. Investigated speed deformation was 2 mm/min.

Specimens were preheated in the chamber until they reached equilibrium with the target temperature. The preheating times were determined from preliminary experiments by an embedded thermocouple, and the prediction model was developed in a previous study (KULMAN and BOIKO 2016). The mechanical properties of the samples were tested in the chamber at the target temperature, results are shown in Table 1.

One hundred fifty specimens were cut from each type of board. Ten specimens were prepared for testing modulus of elasticity (MOE) and rupture (MOR) before main testing. All specimens were conditioned at 20 °C and 65% RH prior to use.

The average densities of specimens were 757 kg/m^3, 792 kg/m^3, and 733 kg/m^3, respectively, in an air-dried condition moisture content of about 5%.

Tab. 1 Properties of particleboard used in study.

Board type	Density [d] kg/m^3	Thickness [d] mm	MOR [d] MPa	MOE [d] MPa
MF PB [a]	757 ± 7	18.1 ± 0.1	17.1 ± 1.1	2 110 ± 29
VF PB [b]	792 ± 8	18.5 ± 0.1	20.5 ± 1.9	2 520 ± 15
P2 PB [c]	733 ± 6	18.1 ± 0.1	16.2 ± 0.6	2 020 ± 22

[a] MF PB – Melamine Faced Particleboard.
[b] VF PB – Veneered Faced Particleboard.
[c] P2 PB – Particleboard according to EN 312, type P2.
[d] Thickness, density, MOR and MOE was measured after specimens reached equilibrium at 65 % RH, temperature 20 °C and moisture content 5%.

Since in the formula (3) the variable factors enter exponentially, the requirements for the accuracy of the experiments on durability should be much higher. Therefore, to obtain reliable statistically significant results in each series of experiments, the number of samples was assumed equal to 30. Five series of tests were carried out for each type of plates. A total of 15 groups were tested. The numbers of replications were 30.

Methods

Based on the numerous studies carried out, we proposed a model of durability taking into account the moisture content of the wood based materials (KULMAN and BOIKO 2015):

$$\tau = \tau_m \exp\left[\frac{U_0 - \gamma\sigma}{RT}\left(1 - \frac{T}{T_m}\right)\right]\exp(\alpha W_e^{-1}) \quad (4)$$

This formula, in addition to external factors such as stress and temperature, contains an effective moisture:

$$W_e = \frac{W_m - W}{W_m} \quad (5)$$

W_m – maximum permitted moisture content of the material in which it has sufficient strength properties for use, %;

W – actual moisture during operation,%; α - coefficient taking into account the impact of moisture content on durability of material.

The values of TAP *(τ_m, U_0, T_m, γ, α)* are determined by solving the system of equations:

$$\begin{cases} \frac{U_0}{RT_1} - \frac{U_0}{RT_m} - \gamma\frac{\sigma_1}{RT_1} + \gamma\frac{\sigma_1}{RT_m} + \ln\tau_m = \ln t_1 - \alpha W_{e1}^{-1} \\ \frac{U_0}{RT_2} - \frac{U_0}{RT_m} - \gamma\frac{\sigma_2}{RT_2} + \gamma\frac{\sigma_2}{RT_m} + \ln\tau_m = \ln t_2 - \alpha W_{e2}^{-1} \\ \frac{U_0}{RT_3} - \frac{U_0}{RT_m} - \gamma\frac{\sigma_3}{RT_3} + \gamma\frac{\sigma_3}{RT_3} + \ln\tau_m = \ln t_3 - \alpha W_{e3}^{-1} \\ \frac{U_0}{RT_4} - \frac{U_0}{RT_m} - \gamma\frac{\sigma_4}{RT_4} + \gamma\frac{\sigma_4}{RT_m} + \ln\tau_m = \ln t_4 - \alpha W_{e4}^{-1} \\ \frac{U_0}{RT_5} - \frac{U_0}{RT_m} - \gamma\frac{\sigma_5}{RT_5} + \gamma\frac{\sigma_5}{RT_m} + \ln\tau_m = \ln t_5 - \alpha W_{e5}^{-1} \end{cases} \quad (6)$$

where T_1, T_2, T_3, T_4 ,T_5 – temperature series of five tests, ^0K; W_{e1}, W_{e2}, W_{e3}, W_{e4}, W_{e5} – effective material moisture content during the five-test series, *%;* σ_1, σ_2, σ_3, σ_4 , σ_5 – modulus of rupture at the appropriate temperature and MC, MPa; t_1, t_2, t_3, t_4 , t_5 – time to rupture at the appropriate temperature (°K) and MC (%), s.

RESULTS AND DISCUSSION

The experimental factors levels and test results are shown in Table 2. 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 moisture content, the strength and modulus of elasticity of the material decreased with increasing the time to failure.

Tab. 2. Experimental factors levels and test results for particleboards.

Board type	Test group number	Test conditions		Test results		
		Temperature (K)	Moisture content (%)	MOR (MPa)	Time to rupture (s)	DML[a] (mm)
MF PB	1	293	6	16.80 ± 1.17 [b]	131.6	4.4
	2	313	8	15.55 ± 0.93	142.6	4.8
	3	333	9	13.80 ± 0.62	184.9	6.2
	4	353	11	11.30 ± 0.15	281.5	9.4
	5	373	15	8.00 ± 0.12	391.5	13.1
VF PB	1	293	6	19.68 ± 0.55	73.7	2.5
	2	313	8	19.00 ± 0.49	85.6	2.9
	3	333	9	17.50 ± 0.38	125.2	4.2
	4	353	11	15.30 ± 0.33	281.5	9.4
	5	373	15	12.00 ± 0.35	665.1	22.2
P2 PB	1	293	6	14.80 ± 0.44	105.6	3.4
	2	313	8	13.40 ± 0.33	140.1	4.6
	3	333	9	11.70 ± 0.21	177.3	5.8
	4	353	11	9.50 ± 0.15	209.6	6.8
	5	373	15	6.00 ± 0.11	344.1	11.2

[a] DML – displacement under maximum level.
[b] The confidence interval is indicated at p = 0,05 level.

For each types, analysis of variance (ANOVA) was conducted to study the effect of temperature and MC on the MOR and time to rupture at a 0.05 significance level. Results of ANOVA and multiple comparison statistical analysis for temperature and moisture content are shown in Table 3.

Tab. 3. ANOVA for bending stress (MOR) and time to rupture for MF PB.

Dependent variable	Source	*SS* [a]	*df* [b]	*MS* [c]	*F* ratio	*p* value
Bending strength (MOR)	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			
Time to rupture	Moisture content	784447.8	4	196111.9	52.85	0.000
	Temperature	70213.0	4	17553.2	4.73	0.010
	Error	59368.6	16	3710.5		
	Total	914029.4	24			

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

The significance value for MOR and for time to rupture between 273 °K and 373 °K, and for moisture content between 6% and 15%, were less than 0.05, indicating that the effect of different temperatures on MOR and time to ruptures 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 time to rupture.

A monotonic, linear and decreasing relationship between the bending strength and the temperature from 20 °C to 140 °C with exposure time of 180 minutes has been reported (BEKHTA *et al.* 2003). In this study however, both the bending strength and MOE showed a substantially nonlinear character of their dependence on temperature and moisture content. The obtained data again confirmed the validity of the phenomenological model of strength of composite materials based on wood proposed earlier (KULMAN and BOIKO 2016).

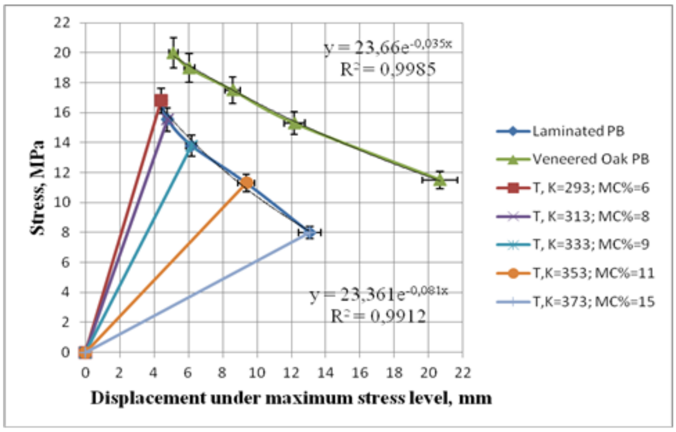


Fig. 1. Summarized ruptures envelope for load-displacement curves for MF PB and VF PB.

Based on the data obtained in the experiments, the thermo-activation parameters (TAPs) for each particleboard type were calculated using the system of equations (5). The results of calculations, as well as earlier obtained TAPs based on long-term tests (BOIKO *et al.* 2013) are presented in Tab. 4.

Tab. 4. Results of calculating the thermo-activation parameters by the defining equations (6).

Board type	Method	*Uo* (kJ/mol)	*lg(τm)* (s)	*γ* (kJ/mol•MPa)	*Tm* (K)	*MCm* (%)	α
MF PB	Shot-Term Test	205	–1.9	8.9	490	19	0.12
	Long-Term Test [a]	196	– 0.7	9.1	486	19	– [b]
VF PB	Shot-Term Test	261	–1.16	11.1	480	20	0.2
	Long-Term Test [a]	257	–0.33	11.4	421	20	– [b]
P2 PB	Shot-Term Test	215	–2.8	10.3	495	21	0.3
	Long-Term Test [a]	213	–2.9	11.3	540	21	– [b]

[a] BOIKO et al. 2013
[b] The procedure of this experiment does not allow to obtain this data.

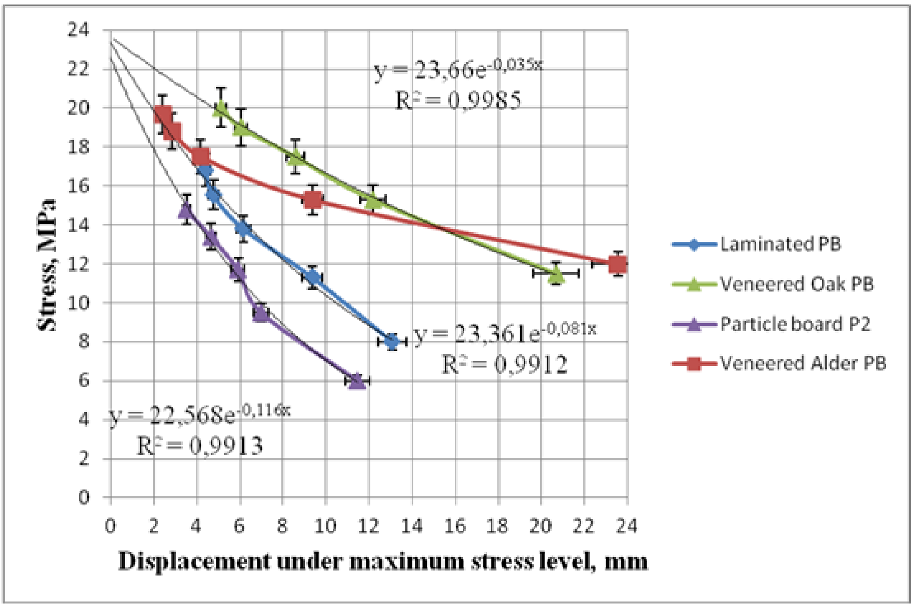


Fig. 2 Changes of mean MOR of particleboards depend on temperature and MC: MF PB – melamine faced particleboard; VO PB – veneered oak particleboard; P2 PB – particleboard according to EN 312 type P2.

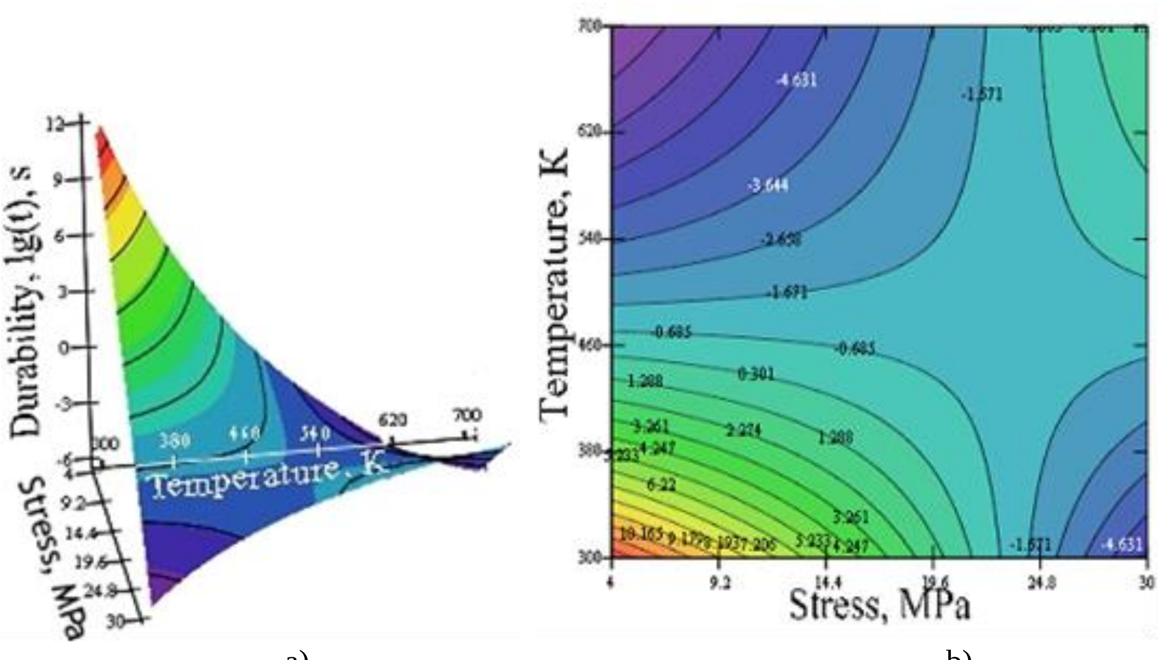
The values of the thermo-activation parameters obtained as a result of the experiments make it possible to estimate the long flexural properties of the PB not only within the investigated range of external factors (load, temperature and moisture content), but to predict the behaviour in a wide range of their variations.

As follows from the results of the experiments (Table 2), the flexural properties of the plates vary with time in accordance with equation (4). Then this connection can most clearly be depicted by constructing a second-order surface corresponding to this equation, assuming one of the factors to be constant.

A computational experiment in the MathCAD environment showed that equation (6) describes a second-order surface, a hyperbolic paraboloid graphically represented in Fig. 3a. The mathematical model of the process of loss of long flexural strength evaluates the flexural properties of the plates, depending on the conditions of their operation. The peculiarity of this surface is that in the phase space of variable factors (σ, T, MC) has a special fixed saddle point - pole. A characteristic feature of this point is that it depends only on thermo-activation parameters (KULMAN 2011).

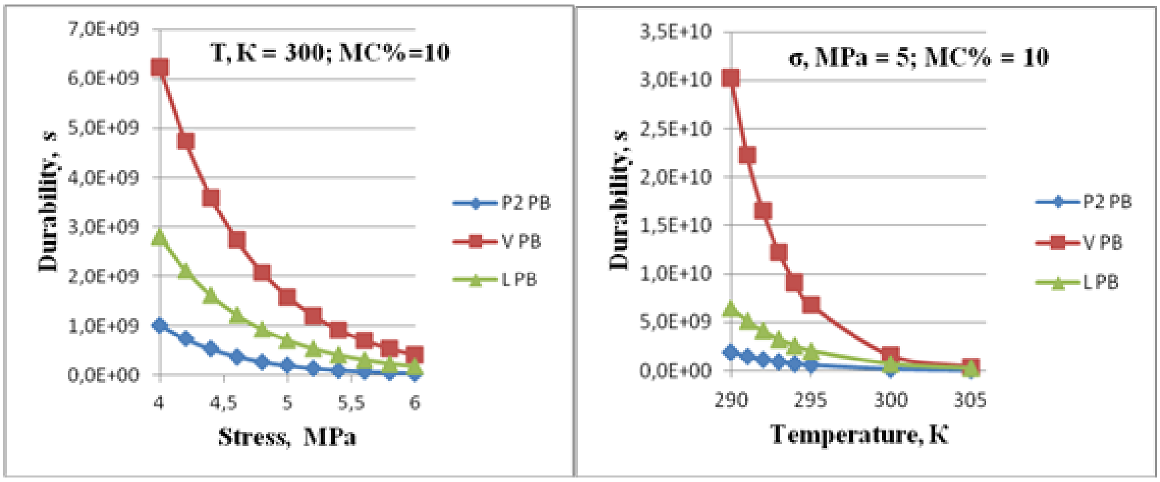
Fig. 3b shows the level lines (contour plot) for a range of variables $T \in 300 \dots 700\ K; MC 10\%;\ \sigma \in 4 \dots 30\ MPa.$

Using the thermo-activation parameters obtained as a result of the experiments, it is possible to estimate the change in the bending properties of PB in time. For example, in Fig. 4a, 4b, 4c are graphs of dependence of the flexural durability of various types of PB depending on one of the varied external factors with relative constancy of two others.



a) b)

Fig. 3 a) Graphical representation of equation (6) in the form of a surface of the second order of a hyperbolic paraboloid. Boundary surface of the long-term flexural strength of a laminated particleboard at a moisture content of 10%; b) Contour plots of bending strength durability for MF PB density 750 kg/m^3.



a) b)

Fig. 4 Dependence of flexural longevity of various types of DCS on external load;
a) – ($\sigma \in 4 \dots 6\ MPa; T = 300\ K; MC = 10\%$);
b – ($T \in 290 \dots 305\ K; \sigma = 5\ MPa; MC = 10\%$).

The analysis of the graphs allows to consider which of the external factors has the greatest impact on the value of the objective function. It can be stated from the graphs, that the durability of laminated boards is more than twice longer as the durability of uncoated PB and twice as much as that of PB lined with natural veneer. In Fig. 5, the graphical form shows the effect of MC particleboard on its durability at constant temperatures and power loading. From the graph follows, that veneered PB is most susceptible to the influence of moisture on strength properties in comparison with laminated PB.

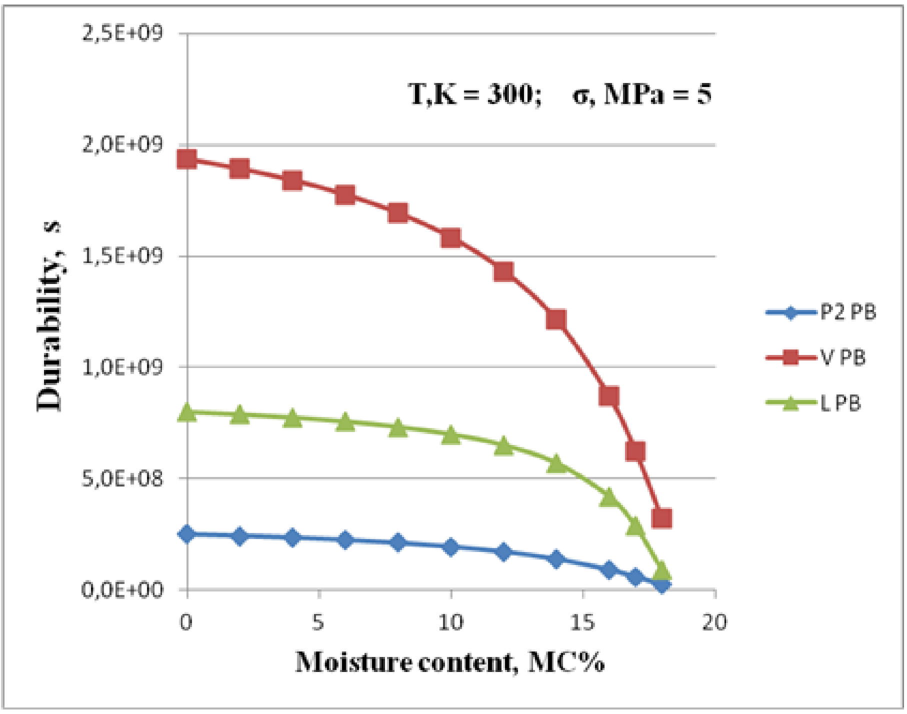


Fig. 5 Dependence the flexural longevity (durability) of various types of PB on the moisture content of the material ($\sigma \in 5\ MPa; T = 300\ K; MC\% = 0 \dots MC_m$).

The graph of the response surface (Fig. 3a) indicates a significant non-linearity of the process of loss of strength in time (with the degradation of the material). This confirms our hypothesis of the nonlinearity of the strength and rigidity of wood-based panels. The reason for the nonlinearity is the interaction of the variables among themselves. However, this requires a special study.

CONCLUSION

The created technique allows considerable reducing time required for testing. The method makes possible to find thermo-activation parameters of the material within changing the thermal and moisture loads. Thus, it becomes possible to estimate the duration of the strength properties of new materials, and to predict the durability in the operation of already created structures.

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ACKNOWLEDGEMENTS

This work was supported by the Ukrainian Ministry of Education and Science under Program No. 2201040: “The research, scientific and technological development, works for the state target programs for public order, training of scientific personnel, financial support scientific infrastructure, scientific press, scientific objects, which are national treasures, support of the State Fund for Fundamental Research”. The authors are grateful to Ministry of Education and Science of Ukrainian for financial support of this study.

This work was supported by the grant agency VEGA under the projects No. 1/0626/16 and 1/0010/17. This work was supported by the Slovak Research and Development Agency under the contract No. APVV-14-0506.

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