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DURABILITY OF KITCHEN FURNITURE MADE FROM MEDIUM-DENSITY FIBREBOARD (MDF)

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ABSTRACT

Furniture products designed of medium-density fibreboard require preliminary assessment of their durability in real conditions. The use of kinetic theory of solid strength was suggested, which had been previously confirmed for particleboard. Developed mathematical model of durability enables to determine the time of destruction of different thickness MDF with different types of surface finishing under the influence of thermal and power loads on panels with moisture content in the range from 6% to 20%. It comprises calculation of MDF thermoactivation parameters based on experimentally determined bending strength and destruction time under temperature ranging from 20 °C to 80 °C. Results of calculations correspond to weighted average service life of furniture intended for kitchen applications.

Key words: medium density fibreboard (MDF), kitchen furniture, bending strength, predicting durability.

INTRODUCTION

European market reflects the increasing tendency to use MDF in a cabinet furniture production instead of particleboard, especially for nursery furniture, kitchen or living room furniture (ENGINEERED WOOD PRODUCTS MARKET SHARE 2021). Kitchen furniture is generally used in adverse temperature and humid environment conditions (HU *et al.* 2020). Given this and the action of mechanical load on the countertop causes bending, probability of cracks and their destruction. High temperature can be as an activator of the destruction and this is a factor reducing durability (GERHARDS 1982; YOUNG and CLANCY 2001; MORAES *et al.* 2005; GREEN and EVANS 2008a and 2008b; AYRILMIS *et al.* 2009). Especially this can be observed in composite materials, which includes resin. The resin has features to change their characteristics over time. The rate of these changes is mainly dependent on temperature. Temperature range of these changes – ageing – is related to glass transition temperature and temperature of other transitions specific to this polymer. Configuration and conformation of macro chain and their supramolecular organization is changing in a result of physical processes. Time factor has an important role in this case (MANIN and HROMOV 1980).

The moisture is a factor that has also an impact on a product durability. As the result of this reaction, macromolecules hydrolytically decompose and properties of the product can be changed. A plasticizer is contributing to polymer secondary structure changes and relaxation of internal stresses (MIRSKI *et al.* 2020). Significant changes of polymeric materials take place under the moisture and heat impact (ZUBAREV *et al.* 2004; MARTENSSON and THELANDERSSON 1990; MOHEBBY *et al.* 2008).

Mechanical load also can be an external activator of loss of durability. It effects both physical and chemical transformations in the material. Mechanical load (static and dynamic) activates physical processes and leads to acceleration of relaxation processes at different temperature and moisture content in composite materials (YU and OSTMAN 1983; SHI and GARDNER 2006). It was found that MDF's modulus of rupture (MOR) and modulus of elasticity (MOE) is decreasing when temperature is increasing (ZHOU *et al.* 2012).

Research on durability of construction materials was carried out during long period. Understanding of solid materials destruction passed through several steps. Current thermoactivation step considers destruction as a process that depends on parameters of defective structure and takes into account thermal motion of atoms. Study of the time-temperature dependence of solid material strength began by ZHURKOV (1965). It has led to formulation of basic principles of kinetic theory of strength of solid materials. Investigations that were conducted in the conditions of single axis tensile for solid materials (single-crystals, poly-crystals, polymers, composite materials) during testing at different temperatures provided an opportunity to identify dependence of durability τ on load σ and temperature T:

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

where: R – universal gas constant (kJ/mol·K); U_0, τ_0, γ – constants of tested material; T – temperature (°K); σ – load (MPa).

Equation (1) is the main for kinetic theory of strength. It has real physical meaning and shows that thermal motion of atoms is the reason of the destruction of solid material. The kinetic theory of strength was used for metals (SLUTSKER *et al.* 2002), HRABAR (2002), for composite materials (REGEL 1980), for polymer fibres and cellulose derivatives (RATNER and YARTSEV 1992). This provided fundamental reasons for using this theory for wood-based composite material – particleboard (HRABAR *et al.* 2008).

Later, a parameter T_m was introduced into the equation (1). T_m is a temperature of destruction, when all bonds in material are breaking during one heat vibration and when substance cease to exist (RATNER and YARTSEV 1992):

$$\tau = \tau_m \cdot exp\left[\frac{U_0 - \gamma\sigma}{R}\left(T^{-1} - T_m^{-1}\right)\right] \quad (2)$$

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); Tm – 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).

It is rational to determine the strength and rigidity of MDF board under the influence of external factors analytically. This will enable to predict the durability of future product during the design process (BOIKO *et al.* 2013).

The aim of this study is to develop the new method of prediction of MDF furniture durability if there is an influence of high temperature and humidity. This method takes into account a long-term action of mechanical load.

MATERIAL AND METHODS

Furniture MDF boards with the thickness of 10, 16 and 19 mm manufactured by JSC "Korostensky MDF Plant" were selected for the study. These panels were without surface finishing, painted and finished by veneer "fine-line". Boards were randomly taken from one consignment of samples according to EN 326-1. It was chosen 40 panels of each thickness at all. Test pieces for physical and mechanical tests (determination of moisture content (EN 322), density (EN 323) and MOR and MOE (EN 310)) were cut from these panels. Before cutting according to EN 325, panels were conditioned at 20 °C and 65% relative humidity.

Average value of panel's density at the moisture content of 5-7 % with the thickness of 10 mm was 824 kg·m^{-3}, for the thickness 16 mm was 811 kg·m^{-3} and for the thickness 19 mm was 802 kg·m^{-3}. Samples of MDF with cross section 10×50 mm, 16×50 mm and 19×50 mm and length 250 mm, 370 mm and 430 mm were used for determination of static bending strength according to EN 310. Tests were carried out at four temperatures 20, 40, 60 and 80 °C by static 3-point bending in the universal test machine, 20 replicates were done. Activation energy was determined using derivatograph according to (STB 1333.0-2002 «POLYMER PRODUCTS FOR BUILDING») with the mass loss of material test portion at temperature during heating with given speed using a range of temperatures. Pine wood (*Pinus*) with moisture content 8 %, MDF panels and urea-formaldehyde resin KF-MT were tested. Experimental plans that included such factors: moisture content within 6-20 %, and temperature action from 5 min to 5 hours (PIZHURIN 2004) were used to test moisture content influence and influence of urea-formaldehyde resin aging on MDF durability.

Equation 2 is used to calculate theoretical durability because it does not take into account influence of temperature changes, humidity, material moisture content and mechanical loads. That's why amendment taking into account exploitation factors are used. Moisture content has the main influence on physical and mechanical properties of wood and wood-based panels, it increases internal stresses and as a result – probability of destruction (KULMAN *et al.* 2017). A lot of external factors influence MDF, which has polymeric binder in its structure. During exploitation, difficult changes take place inside the system of polymer matrix. At first heat treatment leads to material strengthening because the resin is curing, and later to change of physical and mechanical properties. This is taking into account in suggested panel strength model including binder aging (ZAVOROTNUK *et al.* 2020):

$$\tau = \tau_m \, exp\left[\frac{U_0 - \gamma\sigma}{R}\left(T^{-1} - T_m^{-1}\right)\right] exp\left(\alpha\beta \frac{W}{Wm}\right) \quad (3)$$

where: α – coefficient, which takes into account the effect of material moisture content on durability; β – coefficient, which takes into account the degradation of the polymeric binder; W_m – maximum valid value of material's moisture content within which it has sufficient durability properties, (%); W – material's current moisture content during using, (%).

Thermoactivation parameters τ_m, U_0, γ and T_m for MDF are calculated using the equations:

$$\frac{U_0}{RT_{1...4}} - \frac{U_0}{RT_m} - \gamma\frac{\sigma_{1...4}}{T_{1...4}} + \gamma\frac{\sigma_{1...4}}{RT_m} + \ln\tau_m = \ln t_{1...4} \quad (4)$$

where: $T_{1...4}$, – temperature of four testing series, (°K); $\sigma_{1...4}$, – maximum breaking stress at the appropriate temperature, (MPa); $t_{1...4}$ – time to destruction of the sample at the appropriate temperature, (s).

Coefficients α and β were determined experimentally for each type and thickness of MDF depending on the moisture content, the effect of temperature and the time of these factors.

RESULTS AND DISCUSSION

TAP of all testing MDF were calculated by equation system (4) using the Mathcad software, Table 1. Modulus of elasticity in bending and bending strength were tested at different temperatures with time fixation before the destruction of the sample, Table 2.

Tab. 1 Thermoactivation parameters of medium-density fibreboard.

Type of MDF	Activation energy [U_0], (kJ/mol)	Destruction temperature [T_m], (K)	Structural-mechanical parameter [γ], (kJ/ mol·MPa)	Minimal durability [τ_m], (s)
10 mm without finishing	206	409	5.15	0.819
10 mm painted	162	484	5.72	0.733
10 mm veneered	183	425	2.65	0.779
16 mm without finishing	179	440	5.07	0.861
16 mm painted	174	437	4.73	0.811
16 mm veneered	198	432	4.98	0.705
19 mm without finishing	207	411	6.83	0.463
19 mm painted	202	423	6.24	0.905
19 mm veneered	213	396	5.67	0.419

MOR and MOE testing showed deterioration of wood-based composite materials properties within the temperature 60 – 80 °C. MOR and MOE of MDF without finishing with thickness 10 and 16 mm decreased on average at 37.6 % and 33.2 % during temperature rising from 20 °C to 80 °C, Figure 1.

Tab. 2 Test results required to calculate the MDF slab thermoactivation parameters.

No.	MOR, [σ], MPa		Temperature, [T], K		Time until the sample is destroyed, lnτ, s	
MDF 10 mm without finishing						
1	σ_1	38.61	T_1	293	$ln\ \tau_1$	4.304
2	σ_2	33.47	T_2	308	$ln\ \tau_2$	4.174
3	σ_3	31.07	T_3	323	$ln\ \tau_3$	3.932
4	σ_4	27.42	T_4	353	$ln\ \tau_4$	3.584
MDF 10 mm painted						
1	σ_1	39.53	T_1	293	$ln\ \tau_1$	4.143
2	σ_2	31.80	T_2	308	$ln\ \tau_2$	3.932
3	σ_3	31.67	T_3	323	$ln\ \tau_3$	3.689
4	σ_4	30.58	T_4	353	$ln\ \tau_4$	3.219
MDF 10 mm veneered *"fine line"*						
1	σ_1	43.13	T_1	293	$ln\ \tau_1$	4.394
2	σ_2	42.60	T_2	308	$ln\ \tau_2$	4.174
3	σ_3	36.45	T_3	323	$ln\ \tau_3$	3.989
4	σ_4	33.77	T_4	353	$ln\ \tau_4$	3.829
MDF 16 mm without finishing						
1	σ_1	32.34	T_1	293	$ln\ \tau_1$	4.394
2	σ_2	26.21	T_2	308	$ln\ \tau_2$	4.174
3	σ_3	26.82	T_3	323	$ln\ \tau_3$	4.111
4	σ_4	26.88	T_4	353	$ln\ \tau_4$	3.611
MDF 16 mm painted						
1	σ_1	23.48	T_1	293	$ln\ \tau_1$	4.522
2	σ_2	20.87	T_2	308	$ln\ \tau_2$	4.263
3	σ_3	17.96	T_3	323	$ln\ \tau_3$	4.190
4	σ_4	22.78	T_4	353	$ln\ \tau_4$	3.912

MDF 16 mm veneered *"fine line"*						
1	σ_1	27.13	T_1	293	$ln\ \tau_1$	4.369
2	σ_2	25.89	T_2	308	$ln\ \tau_2$	4.263
3	σ_3	24.99	T_3	323	$ln\ \tau_3$	4.234
4	σ_4	21.27	T_4	353	$ln\ \tau_4$	4.159
MDF 19 mm without finishing						
1	σ_1	40.54	T_1	293	$ln\ \tau_1$	4.654
2	σ_2	32.92	T_2	308	$ln\ \tau_2$	4.454
3	σ_3	27.82	T_3	323	$ln\ \tau_3$	4.317
4	σ_4	28.39	T_4	353	$ln\ \tau_4$	4.220
MDF 19 mm painted						
1	σ_1	28.79	T_1	293	$ln\ \tau_1$	4.700
2	σ_2	25.12	T_2	308	$ln\ \tau_2$	4.511
3	σ_3	20.52	T_3	323	$ln\ \tau_3$	4.394
4	σ_4	20.12	T_4	353	$ln\ \tau_4$	4.304
MDF 19 mm veneered *"fine line"*						
1	σ_1	34.94	T_1	293	$ln\ \tau_1$	4.771
2	σ_2	31.99	T_2	308	$ln\ \tau_2$	4.736
3	σ_3	28.52	T_3	323	$ln\ \tau_3$	4.443
4	σ_4	26.83	T_4	353	$ln\ \tau_4$	4.357

* The table shows the average values of a tests series.

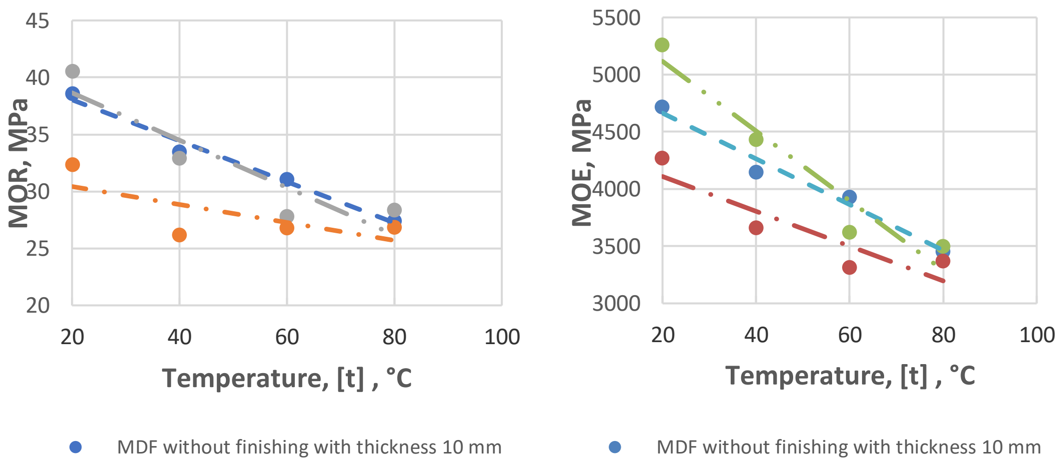

Fig. 1 Graphs of temperature dependence: a) MOR (MPa); b) MOE (MPa).

It was determined that the destruction temperature of MDF is less than the limit destruction temperature of urea-formaldehyde resin, due to the low content of synthetic cross-linked composition in the material (RATNER and YARTSEV 1992). When the composite material destroys, appeared cracks are the result of atomic bonds destruction. The value τ_m characterizes the time during which the process of composite materials destruction occurs at the temperature of destruction. The results of MDF components activation energy determination are shown in Table 3.

Tab. 3 Tested materials activation energy values.

Tested material	Activation energy, [E], kJ/mol
MDF 10 mm without finishing	186
Pine wood	148
UF resin KF-MT	110

It can be seen that the activation energy of the binder has the lowest value, so the process of destruction begins with the resin. This confirmed the hypothesis of the resin aging effect on the durability of MDF, and justifies the addition into the equation (2) of the factor β, which takes into account the effect of UF resin aging. Comparison of the activation energy values determined by the derivative and calculated from the accelerated test showed that they differ on average by no more than 10% for MDF 10 mm thick without finishing (U_0 = 206 kJ/mol).

Adequate experimental data were obtained for calculating the coefficient α of MDF with 10, 16 and 19 mm thick without finishing:

For MDF 10 mm without finishing:

$$\alpha = 0.02 - 0.0008 \cdot W + 0.0028 \cdot \tau - 0.00015\ W \cdot \tau \tag{5}$$

For MDF 16 mm without finishing:

$$\alpha = 0.02 - 0.0011 \cdot W + 0.0055 \cdot \tau - 0.0003\ W \cdot \tau \tag{6}$$

For MDF 19 mm without finishing:

$$\alpha = 0.04 - 0.0017 \cdot W + 0.0042 \cdot \tau - 0.0002\ W \cdot \tau \tag{7}$$

where: W – material moisture content, (%); τ – the duration of the increased value of relative humidity, (h).

Checking the obtained equations for a significance level of 5% confirmed the adequacy of the models (for MDF 10 mm without finishing $F_{calc} = 1.376 < F_{tab} = 3.03$; for MDF 16 mm without finishing $F_{calc} = 0.265 < F_{tab} = 3.03$; for MDF 19 mm without finishing $F_{calc} = 0.813 < F_{tab} = 3.03$).

Based on the results of the studies, a regression dependence was obtained to determine the coefficient of destruction of the resin β from the temperature and time of its action:

$$\beta = 8.14 - 0.0082 \cdot T - 0.0049 \cdot \tau - 0.005 \cdot t \cdot \tau \tag{8}$$

where: T – temperature, (°C), τ – duration of the temperature action, (h)

Both factors and their interaction have a strong negative effect on the destruction of the resin. Verification of equations confirmed the adequacy of the model at the level of 5% significance ($F_{calc} = 2.22 < F_{tab} = 6.0$), all the coefficients of the equation are significant.

According to the results of theoretical and experimental studies, the durability of MDF of different thickness and type of finishing intended for use in the room conditions with parameters t = 20 °C and φ = 60% was determined, Figure 2.

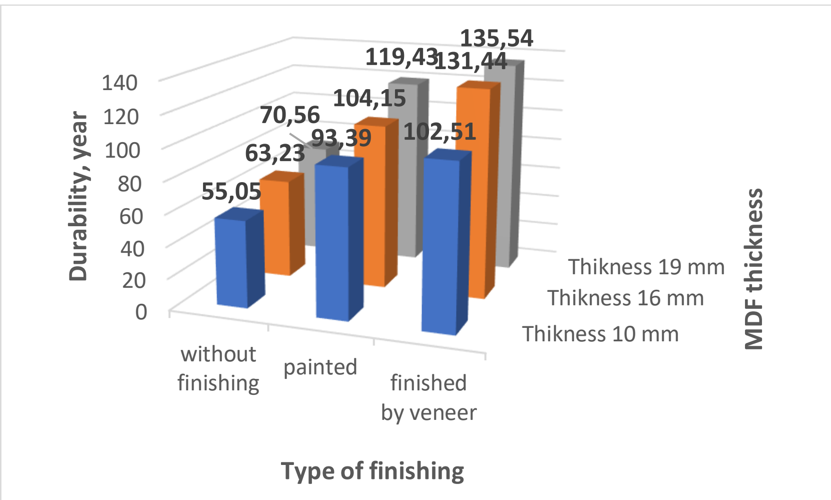

Fig. 2 Durability of MDF with different thickness and finishing type.

Panels surface finishing contributes to the increase in panel's durability of the same thickness, as well as there is a tendency to increase the durability in the case of increasing the thickness of the panels.

The influence of temperature and humidity on the durability of furniture is the most notable when using the kitchen countertops. To evaluate the durability of the countertop, a kitchen set consisted of a cabinet with swing doors, a cabinet for the oven and a hob and a section with drawers for storing kitchen utensils, were considered. The countertop was made of MDF 16 mm thick and finished with natural oak veneer. The case of a curbstone was made from the laminated chipboard 16 mm thick of production "Krono-Ukraine".

To determine the quantitative values of the parameters of equation (3), namely the value of the internal stresses, that occur during the kitchen countertop exploitation, was calculated using the finite element method. It was ensured that the kitchen countertop is rigidly screwed to the lower cabinets. Bottom cabinets were mounted on the floor of the room on supports, which are closed by a plinth. The total weight of household items on the countertop was 20 kg and was evenly distributed. The construction strength criterion is the value of internal stresses that occur during loading and the deflection of the material from which the product is made.

Based on the calculations, the values of internal stresses that occur in the material under the action of uniformly distributed load of 0.16 MPa were determined, Figure 3. Given that the MOR of the MDF is 20 MPa, it can be stated that the material has a considerable margin of safety.

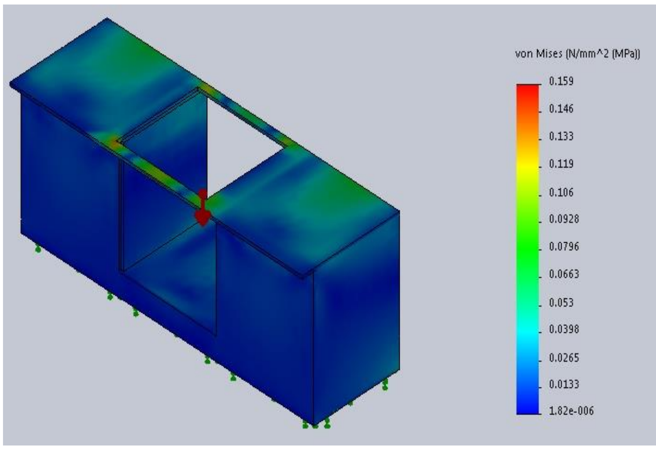

Fig. 3 Stress distributions of the fragment when applying a uniformly distributed load.

The amount of countertop deflection was determined by its deformation by computer simulation in «SolidWorksSimulations», Figure 4.

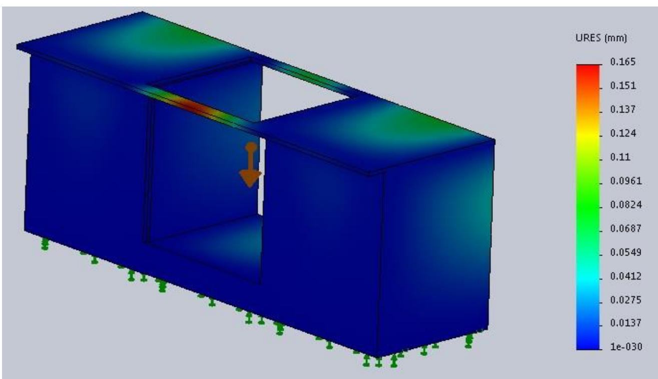

Fig. 4 Movement distribution of the fragment when applying a uniformly distributed load.

When the value of internal stresses is 0.16 MPa, the deformation value is insignificant – 0.165 mm and does not exceed the value of 5 mm, which leaves the required gap between the countertop and the facade.

"SolidWorks Simulations" software was also used to determine the temperature in the area of the hob and oven. The "SolidWorks Simulations" application allowed us to simulate the process of temperature action on a material by setting the initial temperature of the product T = 20 °C and the time during which it would affect the construction τ = 3600 s = 1 hour, Figure 5.

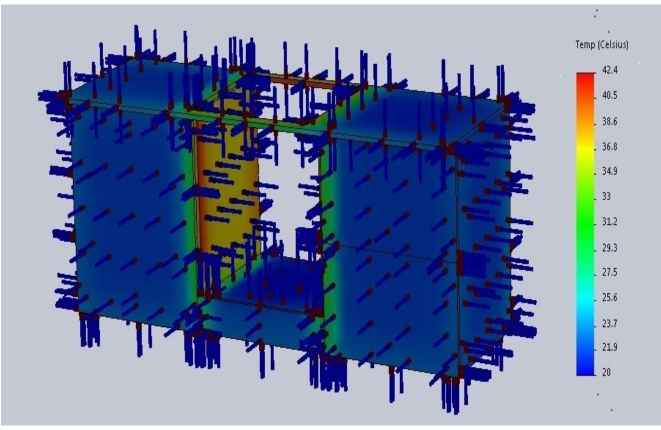

Fig. 5 Simulation of thermal impact in the application «SolidWorks Simulations».

Based on the calculations, it was determined that the temperature has the greatest influence on the side walls of the oven section, where they are adjacent to the oven door and in the contact area of the countertop with the hob. When using the oven and the hob simultaneously for one hour, the maximum temperature was 42.4 ° C.

To check the temperature level obtained from the simulation, experimental studies were carried out with the use of the FLIRi3 thermal imager to determine the temperature field at the junction of the lower table with the countertop to the heating appliances. During the study oven and cooking hobs were switched on, Figure 6.

a) b)

Fig. 6 Sample of kitchen countertop during determining its temperature: a) the sample temperature at the limit of "cooking surface - countertop" at the beginning of heating; b) sample temperature at the limit of "cooking surface - countertop" after 1 hour of oven and cooking hobs working.

The temperature values obtained experimentally (T_{exp} = 44.4 °C) have sufficient similarity to the temperature values obtained by simulation (T_{model} = 42.4 °C). Therefore, the following parameters were accepted for the calculations: load on the hob – 20 kg, causing internal stresses in the material σ = 0.16 MPa, temperature T = 44 °C or T = 317 K, total time of temperature and humidity influence in the kitchen furniture, given that the average daily cooking is 2 hours, then during the year this period of operation will be 30 days.

Observations on the work in the kitchens of residential buildings allowed us to establish that the average duration of the effect of temperature on the kitchen countertop is about 2 hours a day. The result of the calculation with equation (2) and (3) for MDF with different types of finishing are shown in Figures 7–9.

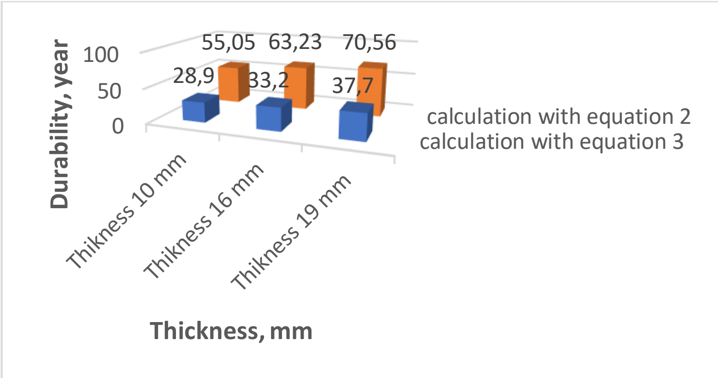

Fig. 7 Calculated durability of the kitchen countertop without finishing.

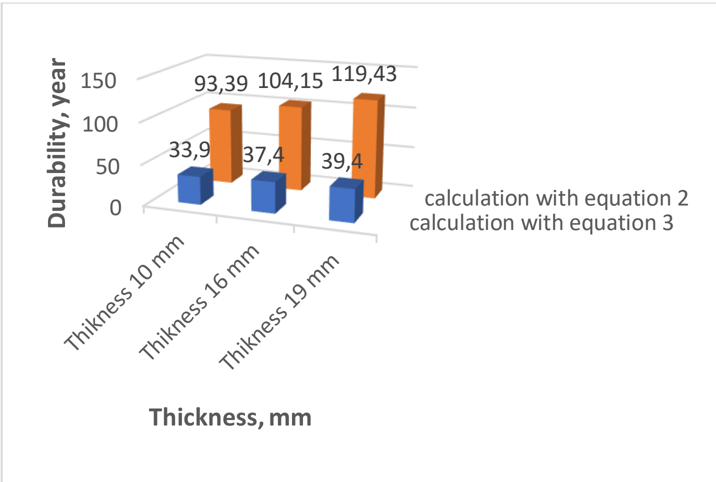

Fig. 8 Calculated durability of the painted kitchen countertop.

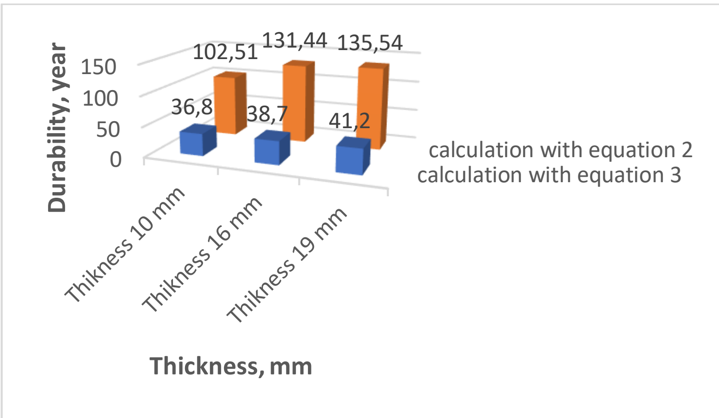

Fig. 9 Calculated durability of the kitchen countertop finished by veneer.

The results of the calculated kitchen countertops durability meet the recommended service life of kitchen furniture, which average 15–20 years.

CONCLUSION

The established technique for predicting the durability of MDF furniture products allows us to find the TAP of the material within the change of heat and humidity load. Application of this methodology can optimize the thickness of MDF and type of surface finishing during the product design. This example of the application of the proposed method for calculating the countertop durability proves the possibility of using thin MDF for kitchen countertops, which meets current trends.

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