

The Influence of Composition and Structure on the Performance Properties of Wood Composites

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Abstract

The paper presents a unified classification of wood composites by structure which makes it possible to better understand the mechanism of destruction. The influence of external structure and composition on the operational properties and durability of wood and wood composites is described. Methods for increasing the operational parameters of wood and wood-based panels are presented.

Keywords

Wood composites; structure; composition; strength; durability; performance.

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Introduction

Currently, wood-based materials are widely used in construction. These materials differ significantly in structure, properties and application. The paper considers the main points connected with this problem.

Structural materials such as natural, modified and laminated wood are widely used in the manufacture of building structures. Plywood is used as elements of building structures: beam walls, dome cover rods, etc. Wood-based panels (plywood, chipboard and fiberboard) have also found application in various enclosing structures as cladding in covering and floor panels, formwork panels, as well as in the construction of frame partitions. In addition, these materials are widely used for interior decoration of living quarters, which contributes to good sound insulation of rooms, significantly speeds up the production of work, reduces labor costs and material consumption, and also excludes wet finishing processes. They are used for filing ceilings in order to create a smooth front surface and improve sound insulation and room acoustics, wall cladding and clean floors. Laminate is the most widely used flooring. Wood-based materials such as chipboard, fiberboard, wood concrete and fiberboard are widely used as thermal insulation. The industry also produces acoustic boards of fiberboard, chipboard and wood concrete.

Classification of wood composites

As mentioned above, wood composites have different structures, therefore, for ease of use, a unified classification of wood-based composite materials was created in [1], which will be useful for obtaining new wood-based materials with desired properties, as well as predicting the performance of existing composites.

According to the type of macro- and microstructure, wood-based composite materials can be divided into five groups (see diagram in Fig. 1).

Wood-based materials can be divided into three classes according to the perception of force effects:

- constructional (wood-laminated plastics, plywood, wood, laminated wood, particle board);
- structural and thermal insulation (chipboard, fiberboard, laminate);
- heat-insulation (wood concrete, fibrolite).

According to the type of binder:

- on a natural binder (wood);
- on a polymer binder (chipboard, fiberboard, plywood, laminate, laminated wood);
- on an inorganic binder (cement particle boards, wood concrete, fibrolite).

The properties of wood composites are widely studied and presented in works [2–4] by such scientists as Mersov, Rebrin, Shvartsman, Khrulev, etc., but practically no attention was paid to the question of their

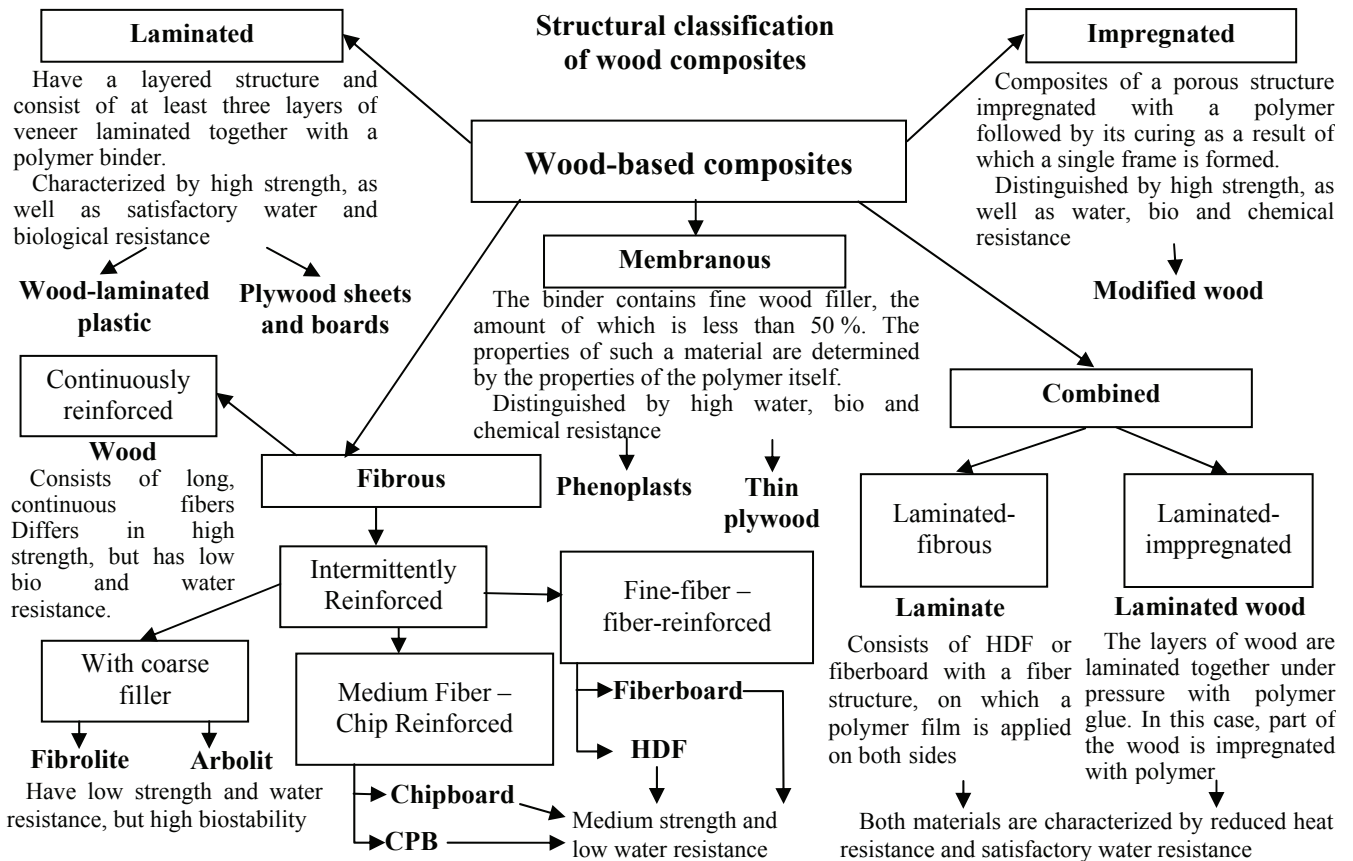


Fig. 1. Classification of wood composites

long-term operation and the effect of the structure on the destruction mechanism, what exactly this article is about.

Wood composites properties

The dependence of the time to destruction (durability τ) of any solids (including wood) on stress σ and temperature T is described by an equation of the Zhurkov type

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

where τ_m , U_0 , γ and T_m are physical constants of the material; τ_m is minimum durability (period of oscillation of kinetic units – atoms, groups of atoms, segments), s; U_0 is maximum activation energy of destruction, kJ/mol; γ is structural and mechanical constant, kJ/(mol×MPa); T_m is limiting temperature of a solid (decomposition temperature), K; R is universal gas constant, kJ/(mol×K); τ is time to destruction (durability), s; σ is stress, MPa; T is temperature, K.

$$\tau = \tau_* \exp\frac{U}{RT} \exp(-\beta\sigma), \quad (2)$$

where τ_* , U – empirical constants; β – structural-mechanical coefficient, MPa^{-1} ,

$$\tau = \tau_m^* \exp\frac{U_0^* - \gamma^* \sigma}{RT} \left(\frac{T_m^*}{T} - 1\right), \quad (3)$$

where τ_m^* , U_0^* , γ^* , T_m^* – empirical constants.

According to formulas (1)–(3) at $s=0$, the durability is finite. This means that destruction can occur at any arbitrarily small load and even in its absence. However, in a number of theories [5] it is assumed that there is some finite stress at which the durability becomes infinitely large. This voltage is called safe. For wood, it is called the limit of long-term resistance and equals 0.5–0.6 of temporary resistance to destruction (tens of MPa). The physical nature of the long-term resistance limit is still not clear, therefore [6, 7] present studies on the influence of various factors on its behavior. An example of the dependence in σ – $\lg\tau$ coordinates is shown in Fig. 2.

The curves have an asymptotic character and their asymptotes determine the values of the long-term resistance limit σ_{lt} .

To reveal the influence of the wood on σ_{lt} , the curves of long-term resistance were constructed at

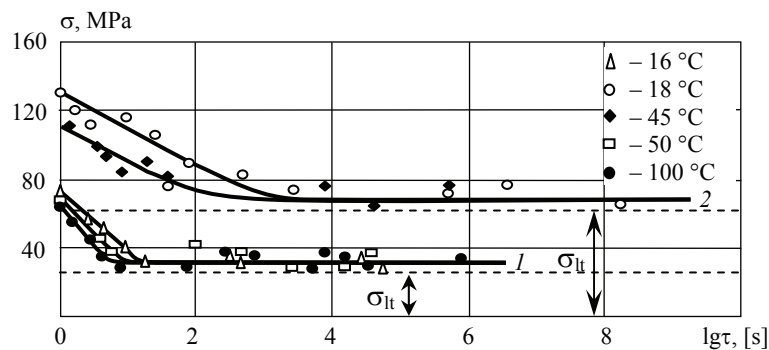


Fig. 2. Influence of temperature on the curves of long-term resistance of uncut pine at longitudinal (1) and transverse (2) bending

transverse bending for undercut and non-cut pine. The structure of the cut pine is characterized by empty resin passages and a lower density of wood, as a result, it has less short-term resistance. But the limit of long-term resistance of undercut and non-cut wood is the same. This shows that the presence of resin in pine does not affect the value of σ_{lt} .

Wood has a complex anisotropic structure at the micro and macro levels. Therefore, when analyzing the reasons for the occurrence of the limit of long-term resistance of wood, it is necessary, first of all, to consider its microstructure.

To understand the mechanism of the appearance of long-term resistance, it is necessary to consider the structure of the wood cell. It has a multilayer shell connected to neighboring cells by the intercellular substance. Experiments on the destruction of wood at the cellular level have shown that the intercellular substance is very strong, and the separation of the cells from each other occurs along the primary layer of the less durable cell, but never along the intercellular substance layer. This allows to assume that the intercellular substance has a structure similar to the structure of high-strength inorganic glasses [5].

High-strength glasses are destroyed by an athermal mechanism, i.e. when the limiting voltage is reached, they are divided into a large number of small fragments. By analogy with high-strength glasses, the intercellular substance, being a binder of wood, is a natural high-strength material with a defect-free structure. When reaching a voltage above the limit of long-term resistance, the intercellular substance is destroyed throughout the volume of the loaded wood sample.

After disintegration of the intercellular substance, the main wood substance is destroyed by the thermofluctuation mechanism (like any other polymers) which manifests itself in a sharp temperature-time dependence of the wood strength (see Fig. 2) at stresses

above the limit of long-term resistance described by equation (3) [7].

Fig. 2 shows that for longitudinal bending σ_{lt} is two times less than for transverse bending. This relationship is obtained by calculating the effective stress based on a linear curve in bending and integrating the stress over the sample volume. Failure during bending occurs in the zone of maximum stresses – in the tension area of the surface layer. Since the resistance to fracture is not exerted by the entire thickness of the sample, but only by this layer, the efficiency of the bending force during fracture should be greater than during deformation. Comparison of the calculated resistances of pine and spruce wood under compression in the longitudinal direction of the fibers and bending in the transverse direction also gives a value of 0.7.

The most important for understanding the physical nature of the long-term resistance limit is to study the effect of temperature on it. As tests have shown, the limit of long-term resistance of wood does not depend on temperature (see Fig. 2), which confirms the athermal mechanism of its destruction when σ_{lt} is reached.

The paper makes an attempt to examine how the structure of the material affects the long-term properties of wood materials.

The regularities of destruction and deformation of wood and materials based on it are considered under prolonged loading and temperature variations. During the tests, the time until destruction or achievement of a given deformation (10 %) was recorded, which, according to [8], is the limiting one during the operation of heavily loaded wooden structures. Examples of the results obtained are shown in Figs. 3–5. Long-term tests were carried out under different types of loading: transverse bending, compression, shearing – in the mode of specified constant stresses and temperatures.

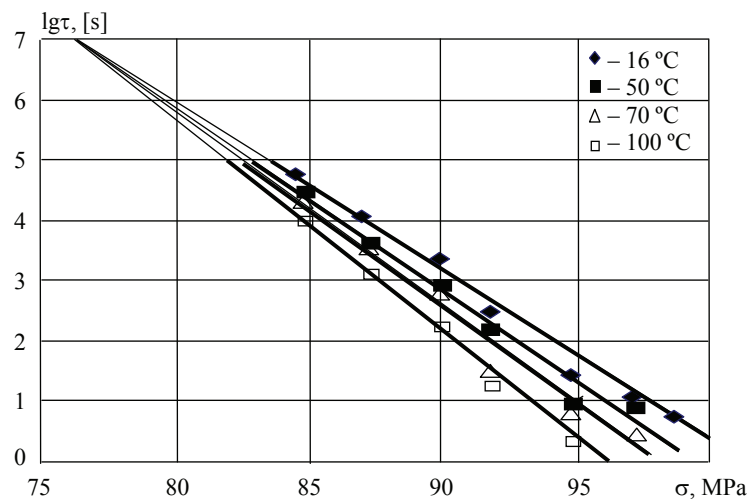


Fig. 3. Dependences of pine durability on stress and temperature during transverse bending

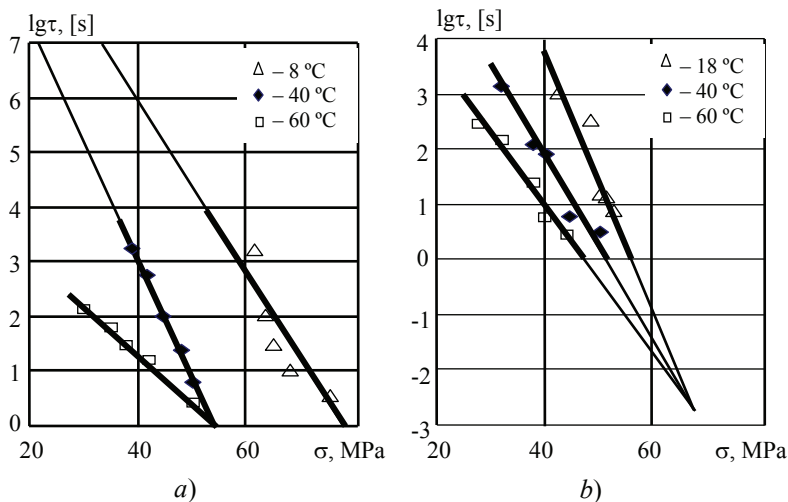


Fig. 4. Dependences of durability on stress during transverse bending for laminated wood:
a – 2-layer; b – 3-layer

Fig. 3 shows that the nature of the dependence obtained for wood differs from the classical one: it forms families of straight lines converging at a pole not at high, but at low stresses, which is apparently associated with the orientation of cellulose fibers. Equation (2) is used to describe this dependence.

In contrast to solid laminated wood in the studied temperature range, it has a complex mechanism of destruction and deformation. For two-layer laminated wood with transverse bending (Fig. 4a) and compression (Fig. 5) in the temperature range up to 40 °C, the dependences represent a reverse bunch, and at temperatures above 40 °C – a forward bunch. For three-layer laminated wood, the $\lg\tau$ - σ dependence has the form of a straight bundle (Fig. 4b). Apparently, this behavior of laminated wood is associated with its laminated macrostructure [7, 9]. In the temperature

range from 8 to 40 °C with one glue joint, the bearing and deformation capacity is determined by wood, and above 40 °C and with an increase in the number of glue layers (for three-layer wood) – by glue [10].

When chipping, the dependences ($\lg\tau$ - σ) have the form of a straight beam, which confirms the decisive role of the adhesive layer in the bearing capacity of wood over the entire temperature range. So at a temperature of 18 °C, 50 % of the samples collapsed along wood, and the rest along the border of wood and glue. With an increase in temperature (up to 40 °C and above), destruction occurred only along the glue line, which is unacceptable. At the same time, the durability fell by 3–4 orders of magnitude.

We also considered the behavior of wood in a complex type of stress state – penetration (i.e. the introduction of a solid), which includes both the

processes of destruction and deformation [11]. To reveal the macromechanism of wood behavior during the introduction of a steel indenter in the form of a sphere of $\varnothing 10$ mm, the penetration process was considered from the thermal fluctuation positions [12]. For this purpose, at given temperatures and loads, the dependences of the deformation durability τ (the time of immersion of the indenter in the material by 1 mm) on hardness H were obtained. The test results have a form similar to the dependences shown in Figs. 3, 4.

The constants included in equations (1) and (3) were determined by the graphical analytical method and their values are presented in Table. 1.

The table shows that all constants change during the destruction and deformation of laminated wood in comparison with solid wood. Moreover, their values depend on the number of joints in the section. For a straight beam with transverse bending and shearing in the studied temperature range 40–60 °C, T_m is close in value to the softening temperature of polymer glue, while U_0 corresponds to the breaking energy of intermolecular [10], but not chemical bonds. This indicates the decisive role of the deformation processes during fracture which was confirmed by visual observations: before fracture the samples were strongly deformed. For three-layer wood, the pole temperature corresponds to the decomposition temperature of the adhesive joint, and the maximum activation energy is close to the activation energy of the polyvinyl acetate destruction [7]. When the load type changes, two constants change sharply – U_0^* during

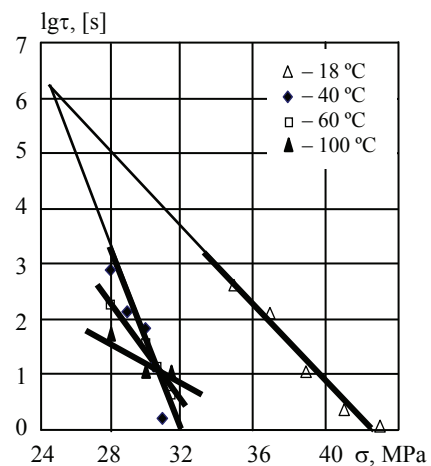


Fig. 5. Dependences of durability on compression stress for 2-layer laminated wood

chipping increases by approximately 1.5 times, while γ^* decreases by almost 13 times. This is due to the load type and the deformation processes. During transverse bending, the samples are significantly deformed before fracture, which is accompanied by the movement of segments in wood, which requires the simultaneous breaking of several tens of van der Waals bonds. A sharp change in γ is also associated with the load type, since $\gamma = \gamma_{lt}\gamma_d$ (where γ_{lt} – the component of the load type, γ_d – the deformation component). The ratio γ_{lt} in bending and shearing for many structural materials is 1.7 [14]; then the deformation

Table 1

Values of empirical and physical constants for solid and laminated wood under different load types

Load type	Section view	Number of joints	Temperature interval, °C	Physical constants			
				$\tau_m, \tau_m^*,$ s	$T_m, T_m^*,$ K	$U_0, U_0^*,$ kJ/mol	$\gamma, \gamma^*,$ kJ/(mol×MPa)
Transverse bending	Solid	–	18–100	10^7	160	–131	–1.7
	Laminated	1	8–40	10^{18}	200	–65	–2.24
		2	40–60	$10^{0.6}$	343	752	14.64
Shearing	Solid	–	18–40	$10^{-2.6}$	438	301	4.38
	Laminated	1	16–100	10^7	200	–80	–21.6
	Solid	–	16–100	$10^{-4.8}$	348	623	86.27
Compression	Solid	–	16–100	$10^{0.32}$	566	120	4.08
	Laminated	1	18–40	$10^{6.18}$	276	–927	–36.9
Penetration	Solid	–	40–100	$10^{0.98}$	418	342	10.71
		–	16–100	$10^{-0.4}$	630	244,6	9.04

component γ_d is equal to 7, which led to such a change in the value of the structural-mechanical constant. The constants (τ_0^* , T_0^*) practically do not change with a change in the load type [14].

Under compression of wood, the value of T_m coincides with the initial temperature of cellulose decomposition [10]. The great value of the preexponent is associated with the period of oscillation of the segments of wood macromolecules. A small value of the activation energy indicates a small number of links moving at a time at a deformation of 10 %. Therefore, 10 % deformation for wood is not critical.

During deformation by compression of the laminated section in the temperature range of 40–100 °C in comparison with the solid section, all constants also change. This is especially pronounced in the values of the activation energy U_0 and the structural-mechanical constant γ . In the temperature ranges 18–40 °C and 40–100 °C above $\sigma = 31$ MPa (Fig. 5), the nature of the dependence changes, which is apparently associated with structural changes in the adhesive layer [9].

During wood penetration, the activation energy of the process is close to U_0 for the destruction of chemical bonds of cellulose. The value of γ also indicates the leading role of the destruction processes, while T_m corresponds to the decomposition temperature of cellulose. To sum it up, we can conclude that during the penetration of wood, a complex interweaving of two processes is observed: destruction and deformation. However, destruction is decisive [15].

Thus, the mechanical behavior of laminated wood under long-term loading differs significantly from solid wood [1, 15]. Therefore, to make certain adjustments to SNiP II-25-80 “Wooden structures. Design Standards”, it is necessary to conduct a comprehensive study of the durability and long-term strength of laminated wood in a wide range of loads and temperatures, as well as under the additional influence of physico-chemical and climatic factors.

To increase the main parameters of the performance (durability and long-term strength) of wood, it is necessary to control physical and empirical constants in a targeted manner – to increase U_0^* , τ_m^* , T_m^* and decrease γ^* .

As shown in [10], the value of U_0 depends not only on the breaking energy of chemical bonds in organic material, but also on the kinetics of the thermal destruction process which leads to mechanical destruction. The introduction of substances into organic material that weaken the rate of thermochemical

destruction will increase the value of U_0 and, accordingly, the performance of the material. It was experimentally found that the value of U_0 significantly increases with the introduction of effective thermal and photo stabilizers. On the contrary, the introduction of a substance that accelerates the destruction, decreases U_0 . As for the value of γ , it changes with the introduction of solid fillers and liquid plasticizers [24].

One of the effective methods for influencing the material constants in this way is modification. Most often, polymers are used for wood modification (phenolic-aldehyde, resorcinol-formaldehyde, urea-formaldehyde, melamine-formaldehyde, organosilicon, furan, unsaturated polyesters) and monomers (styrene, methyl methacrylate) [4, 16]. Sulfur and paraffin have also proven themselves well [4].

Currently, there are many works devoted to the study of the effect of modifiers on the physico-mechanical characteristics of wood. However, they do not address issues related to the behavior of modified wood over time. To reveal the behavior of modified wood under operating conditions in the mode of specified stresses and temperatures under two load types (transverse bending and penetration), dependences were also obtained in the coordinates $\lg\tau-\sigma$ and $\lg\theta-H$. The results obtained are shown in coordinates in Fig. 6.

When wood is modified with kerosene, the dependence from the reverse beam (obtained for pure wood) (see Fig. 3) to the direct one (Fig. 6) changes. Apparently, this behavior is associated with the organization of a more homogeneous structure in the modified wood. This is confirmed by micro-optical studies, the results of which are shown in Fig. 7 [7, 17].

The durability of kerosene-modified wood at room temperature is higher, and at elevated temperatures it is lower than that of pure wood, which, apparently, is associated with the activity of the modifier and its partial evaporation over time.

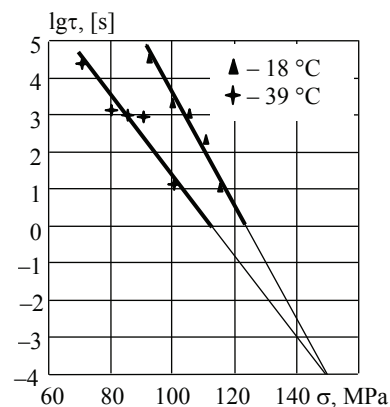


Fig. 6. Dependences of durability on transverse bending stress for kerosene-modified wood

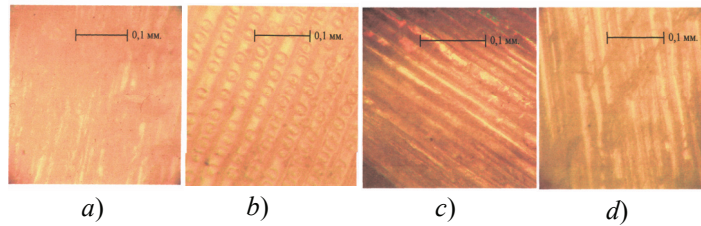


Fig. 7. Optical micrographs of wood structure before and after modification:
a – initial; *b* – Emucryl C-modified wood; *c* – emulsion 252-modified wood; *d* – kerosene-modified wood

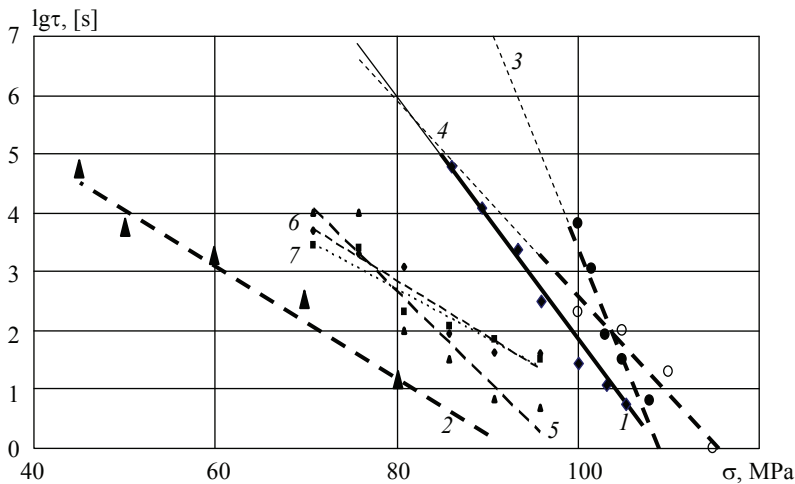


Fig. 8. Dependence of durability at 18 °C on the transverse bending stress for pure (I) and modified wood:
 2 – with emucryl C during heat treatment for 6 hours; 3 – the same for 10 hours;
 4 – with kerosene; 5 – with emucryl M; 6 – with emulsion 252; 7 – with paraffin

Straight lines $\lg\theta-H$ and $\lg\tau-\sigma$ obtained during long-term operation of modified wood with transverse bending and penetration are plotted on the dependence of durability on hardness (or strength) for pure wood (Figs. 8, 9) [15].

Fig. 8 shows that after modification with kerosene at room temperature and emucryl C (with additional heat treatment for 10 hours), the durability of wood increases, and for wood impregnated with emucryl C (with 6 hours heat treatment) it decreases. With an increase in the duration of heat treatment of wood impregnated with emucryl C, a change in the slope of the $\lg\tau-\sigma$ straight lines is observed, which also indicates structural changes in the wood. The durability of natural and kerosene-impregnated wood coincides at 75 MPa, which, apparently, is associated with the evaporation of kerosene [7].

The introduction of paraffin into wood leads to an increase in deformation durability by 2–4 orders of magnitude at stresses (hardness) above 13 MPa, and at hardness of $H = 13$ MPa, while the durability of natural

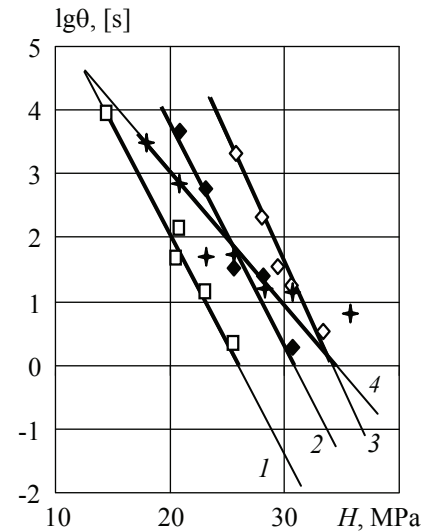


Fig. 9. Dependences of deformation durability on hardness for pure (I) and modified wood
 (2 – with kerosene; 3 – with emucryl C; 4 – with paraffin)

and modified wood is the same (Fig. 9). Modification of wood with kerosene and emucryl C also leads to an increase in its long-term hardness and deformation durability. In this case, the slope of straight lines does not change [7].

Depending on the operating conditions, it is possible to recommend: for wooden structures operating in conditions of high humidity, to use any of the studied substances as a modifier; and for load-bearing wooden structures – kerosene, paraffin or emucryl C.

As it was mentioned above, Zhurkov's concept of the polymer destruction mechanism and formulas (1) – (3) provide the basis for regulating the physical constants that determine the performance of polymer materials in accordance with the principle of temperature-time force equivalence. One of the promising methods for increasing the performance of a polymer is its filling [18]. The introduction of the filler helps to increase the rigidity, strength, hardness, heat resistance and impart some special properties to the

composite, for example, chemical resistance, aesthetics. The degree of shrinkage constraint, the value of internal stresses and the intensity of adhesive interaction depend on the shape, size and nature of the fillers. By activity, fillers can be divided into active and inactive (inert).

Filler grains in a system that tends to reduce surface energy are combined into clusters of various sizes, which are elementary structural cells and exist in the binder along with non-aggregated particles. The elementary cells of the structure in the process of their growth form blocks with a cross section in the form of a hexagon close to spheres. Combining cells into clusters leads to structures of higher levels, which, in turn, are part of larger structural blocks, ultimately determining the polystructurality of solid composites. At the same time, at the optimum grain size, interpenetration and coalescence of binder and filler clusters and the formation of endless clusters occur. Such a state of the system at optimal saturation provides strengthening of the filled structure. There is a significant compaction of the binder inside the clusters and its decompaction in the peripheral regions [19].

Another, no less important indicator is the presence in the volume of the material of a space frame made of filler particles held together by a matrix membrane.

With an increase in the content of fillers, the matrix begins to pass gradually from the bulk state to the membranous state, and at the end of the primary bifurcation (bifurcation – appearance of branches during the formation of linear clusters) this process ends. With further filling in the bulk of the composition, the membrane matrix becomes discontinuous, transforms into thin membrane islands on the areas of the filler surface, which leads to a decrease in the strength of the composite as a whole [19].

In [10] it was found that during filling, an increase in the values of τ_m and T_m (Figs. 10, 11) and a decrease

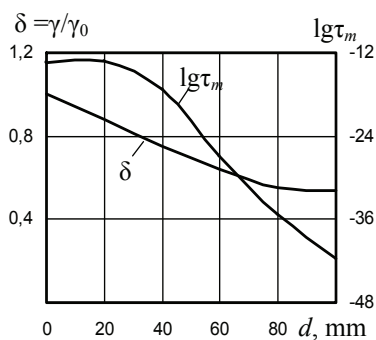


Fig. 10. Dependence of plastics physical constants on the average particle size of the filler

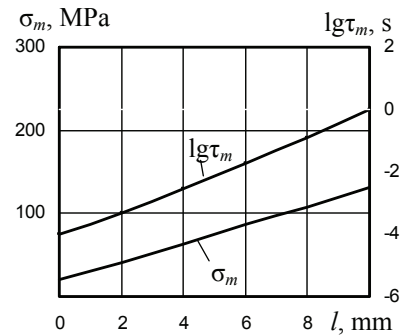


Fig. 11. Influence of filler fiber length on plastics strength constants

in the value of the structural coefficient γ are observed, which in turn leads to an increase in the main parameters of the performance of composites. The value of U_0 remains unchanged only when inert fillers are introduced up to some critical value.

A significant increase in τ_m with a large amount of filler is apparently associated with the transfer of an elementary act of destruction not from one polymer chain to another, but bypassing filler particles.

When choosing a filler, the following factors must be also considered. The binder and filler must have the same temperature coefficients of linear expansion and shrinkage values, otherwise thermal and shrinkage stresses will appear in the composite, which in turn will lead to the appearance of seed cracks.

The strength of composites is significantly influenced by the dispersion of the filler. In some cases, for increasing the strength of PCMs, dispersion is of greater importance than the chemical nature of the filler or modification of its surface. If the strength of the composite decreases under the influence of the filler, then often this decrease can be reduced or completely compensated by an increase in dispersion. When a crack interacts with particles commensurate with the structural units of the matrix, they are unable to create extended zones of influence in the matrix and thus bend and increase the length of the crack.

However, an excessively high dispersion of the filler is also undesirable because it increases its tendency to aggregate in dry form. Small gaps between the particles prevent the polymer binder from flowing into aggregates. As a result, during polymerization, aggregates of filler particles are encapsulated in a polymer matrix, which leads to a decrease in the mechanical properties of composites [19].

As indicated in [10, 12], an increase in the average size of filler particles leads to a decrease in the values of γ and τ_m (Fig. 10), and fillers with an average particle size of 50–200 μm have the greatest strengthening effect.

The introduction of fibrous fillers leads to an extreme change in the mechanical properties of polymer composites [10]. So the activation energy U_0 changes abruptly when the content of the reinforcing fiber in the composites is greater than the critical value of v_{cr} . So, for phenolic resin, in which phenol-formaldehyde resin is 50 %, U_0 is equal to 112 kJ/mol, i.e. activation energy of the resin, while for particle board (resin 10 %) U_0 is on average 220 kJ/mol, which corresponds to the activation energy of cellulose. During filling, the maximum destruction temperature also increases [20]. An extreme increase in U_0 is also observed for a fiber length greater than l_{cr} :

$$l_{cr} \approx \frac{d\sigma_{fib}}{2\tau_{shear}} \approx 10^3 d,$$

where d – fiber diameter; σ_{fib} – fiber strength; τ_{shear} – shear strength of the fiber-polymer bond.

Chipboard can serve as an example. For chipboard with large chips, the activation energy U_0 is close to the value of U_0 for cellulose, and with a decrease in the chip length, the activation energy becomes close to the value of U_0 of phenol-formaldehyde resin [1, 10].

In [14], the minimum and maximum critical fiber lengths were established: $l_{cr\ min} \approx 1$ mm, $l_{cr\ max} = 10$ mm. When the fiber length changes from 1 to 10 mm, U_0 takes on values that are multiples of E_{fib} , i.e. $U_0 = nE_{fib}$, where n is the number of chemical bonds in the glass fiber that are broken during one thermal fluctuation. With an increase in the length of the reinforcing fiber, the number of bonds between the polymer and the filler increases, on which the applied load is distributed. Therefore, the stress concentration coefficient χ decreases and the fluctuation volume changes extremely.

However, the introduction of a plasticizer improves the technological parameters of composites processing and improves adhesion. In addition, by reducing the viscosity of the binder, it is possible to introduce a larger amount of filler, which also makes it possible to reduce the cost of composites [19].

Thus, the kinetic concept of strength and deformation opens up ample opportunities for the targeted development of polymer composite materials with predetermined properties and for predicting changes in their main parameters of serviceability (force, temperature, and time) during operation.

The sizes of the AFO particles (40–120 μm), selected as the second filler, lie in the recommended optimal range (50–200 μm). Therefore, their

introduction will make it possible to obtain a strengthening effect and to achieve an increase in the water resistance of the composite by reducing the amount of porous filler, i.e. wood. The content of the fibrous filler, due to its reinforcing action, will lead to the preservation of rigidity and strength when cutting the composites. The presence of mineral fillers should also have a positive effect on the thermal stability T_m , which, in general, will provide an increase in the main operational parameters of composites [20].

The introduction of polymer dispersed fillers (rubber and expanded polystyrene crumbs), due to the close chemical nature of the binder, should not affect the values of the constants U_0 and T_m . In this case, the value of the activation energy will be determined by the properties of the wood filler at a high content. An increase in the damping and thermophysical properties of composites is also expected. Due to a decrease in internal stresses in the polymer, an increase in the parameter γ is possible [1].

With the plasticization of the MSE, a decrease in the thermal resistance T_m is expected, and due to an increase in the elastic properties of the polymer there will be an increase in the constant γ , which will lead to a decrease in the performance parameters of the composites. However, in this case, a decrease in the viscosity of the binder will be observed allowing an increase in the content of the filler, as well as increasing the strength of the composite by improving the adhesion of the filler and the resin.

To reveal the effect of the filler (its size and type) on the regularities of the destruction of wood composites in [1, 21], the dependences in the coordinates of the durability logarithm on stress were presented in Fig. 12–15.

Fig. 12 shows that for particle boards with a density of 650, 700 and 850 kg/m^3 , the obtained linear dependences form families of straight lines (beams) converging at one point (pole) and are described by equation (1) [1, 22].

For a chipboard with a density of 800 kg/m^3 filled with small chips, the form of the dependence changes, a family of parallel straight lines is formed (Fig. 12), which is precisely related to a decrease in the average size of the filler [21]. This behaviour can be explained by a change in the structure during the test (a change in γ according to a certain dependence) due to additional bonds, the role of which in chipboard is apparently played by the adhesive bonds phenol-formaldehyde resin – wood. The presence of additional bonds is the reason for the increased heat resistance of the boards. This dependence is described by equation (2).

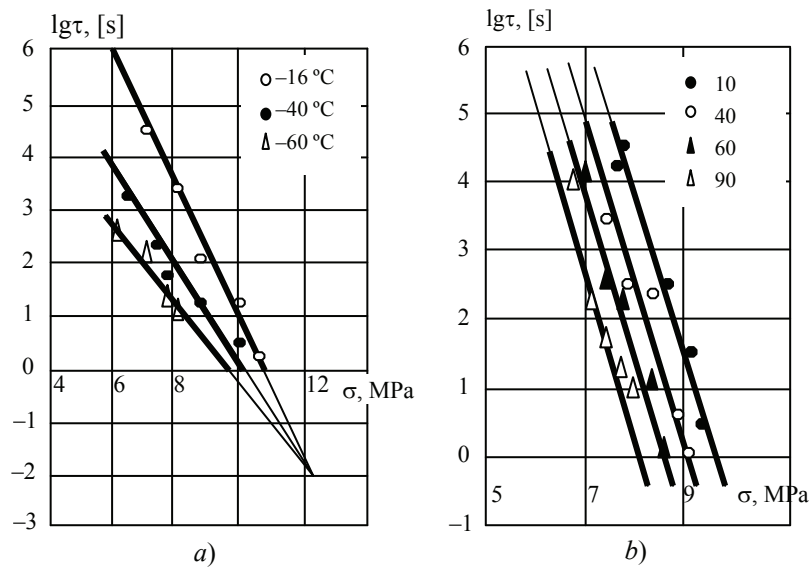


Fig. 12. Dependence of durability on stress during transverse bending for chipboards with a density of: a – 850; b – 800 kg/m³

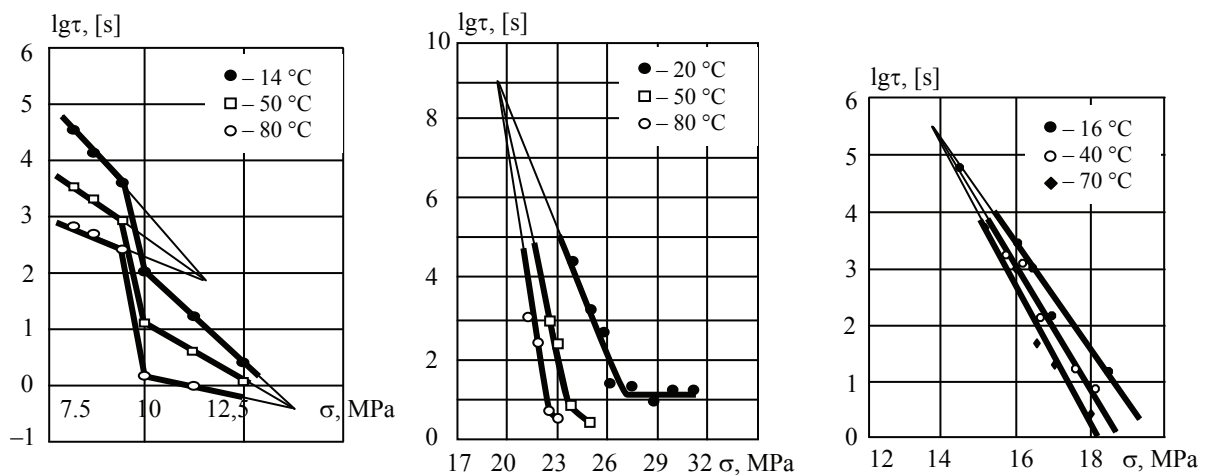


Fig. 13. Dependence of durability on stress in transverse bending for fiberboard with a density of: a – 200–350; b – 850; c – 950 kg/m³

For solid fiberboard with a density of 850 and 950 kg/m³ (Fig. 13), the dependences take the form of a backward beam and are described by equation (3). This kind of dependence for solid fiberboard is associated with the orientation of the wood fibers and its change during the test.

Thus, an increase in the homogeneity and orientation of the filler in wood-based panels leads to a change in the nature of the dependences reflecting the process of destruction under prolonged exposure to constant loads and temperatures. There is a transition from a “straight beam” (particle boards) to parallel straight lines (chipboard with fine chips) and then to a “reverse beam” (hard fiberboards) [1].

For soft fiberboard, the experimental dependences are complex [21]. Thus, in the $lg\tau-\sigma$ coordinates, a

break is observed on the straight lines, and in the $lg\tau-10^3/T$ coordinates, two beams are formed. This, apparently, is associated with the mechanism of destruction: at low stresses, the determining factor is the layer-by-layer destruction of individual fragments of the board, and at large stresses, it works monolithically, which is confirmed visually in the plane of the sample destruction.

A complex mechanism of destruction is also characteristic of plywood and laminate (Figs. 14, 15). Thus, at low stresses, layer-by-layer destruction of plywood occurs (for the FSF grade at $\sigma < 80$ MPa, and for FC grade – < 130 MPa), while in the high-stress range it works as a monolithic material. In addition, FSF plywood works differently in the temperature ranges before and after 40 °C, which is apparently

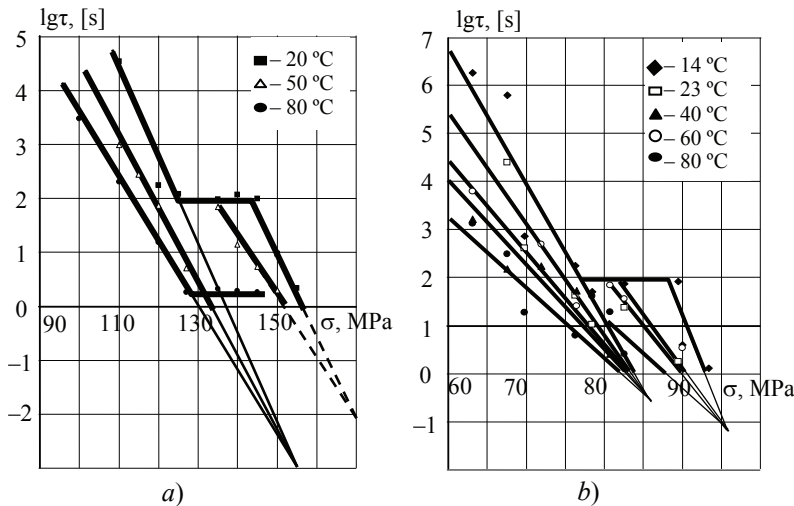


Fig. 14. Dependence of durability on transverse bending stress for plywood of grade:
a – FK; b – FSF

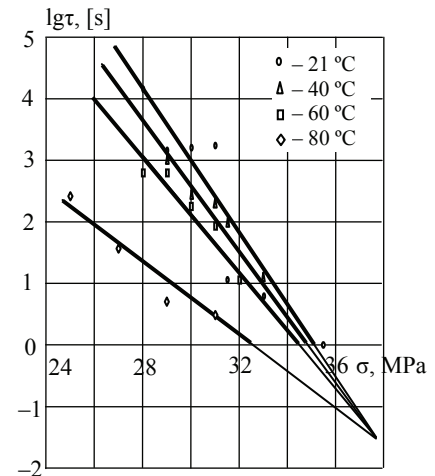


Fig. 15. Dependence of durability on transverse bending stress for laminate

associated with a change in the state of the resin which undergoes additional curing at elevated temperatures. In this case, all dependences are in the form of a direct beam [1, 21].

Laminate works differently in temperature ranges up to +60 °C and above. This behavior is precisely due to its structure. It is a hard fiberboard or HDF lined on both sides with a polymer film that performs a protective function. In the first case, the performance of laminate is determined by fiberboard. The polymer film, apparently, breaks down brittle, which is indicated by the large scatter of experimental results. At elevated temperatures (+40 °C), it turns into a viscous-flowing state and starts working, which leads to an increase in the stability of the laminate strength. In this case, the shape of the strength scatter curve is preserved, but its area decreases (Fig. 16). However, the polymer film begins to exert a significant influence on the performance of laminate only at temperatures above 60 °C [1]. The presence of a phase transition is also

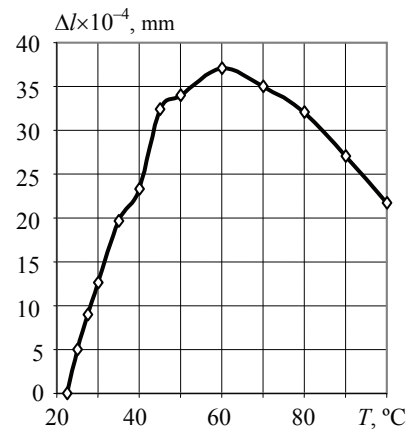


Fig. 17. Dilatometric curve of laminate

confirmed on the dilatometric curve (Fig. 17). The figure shows that a break occurs on the graph at a temperature of 45 °C, the process of sample elongation slows down, and after 60 °C they begin to narrow.

According to the obtained dependences, physical and empirical constants were determined by the graphic-analytical method using the Konstanta program, the values of which are presented in Tables 2 and 3.

The table shows that for all tested materials pre-exponential τ_m is much larger than the period of atom vibrations in a solid (10^{-12} s) and is in the range of $10^{-3.2}$ – $10^{9.4}$ s. This is explained by the fact that wood composites have a complex composition and structure, therefore, the crack path increases due to bending around the filler particles [10].

The pole temperature T_m of chipboards corresponds to the critical decomposition temperature of phenol-formaldehyde resin ($T = 553$ – 563 K) [10].

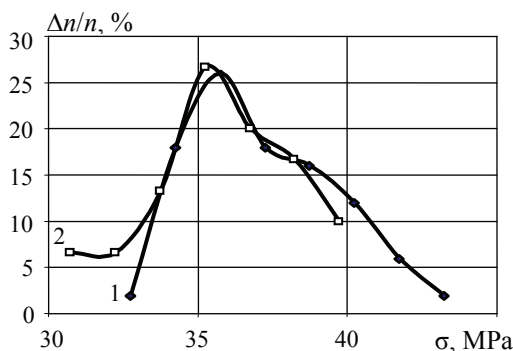


Fig. 16. Variation laminate strength (Kronospan) class 31:
1 – at 20 °C; 2 – at 40 °C

Table 2

Values of physical and empirical constants for transverse bending

Material	Density, kg/m ³	Load type	Direction of the force action relative to the surface of the board	Physical and empirical constants				Performance parameters			
				τ_m (τ^* , τ_m^*), s	T_m (T_m^*), K	U_0 (U , U_0^*), kJ/mol	γ (γ^*), kJ/(MPa·mol)	β , MPa ⁻¹	τ , s	σ , MPa	T , K
Chipboard	650	Transverse bending	Perpendicular	10^{-3}	571	194	12,8	–	$10^{5.6}$	8.1	299
			Parallel	$10^{-3.2}$	465	244	16,7	–	$10^{4.4}$	7.4	–
	700	Transverse bending	–	$10^{-2.9}$	540	213	11,3	–	$10^{7.8}$	10.5	328
			Compression	–	$10^{-0.95}$	368	474	41,8	–	$10^{5.1}$	7.7
	800	Transverse bending	–	$10^{9.4}$	–	70	–	2,25	$10^{4.88}$	7.4	285
			Compression	–	$10^{6.25}$	189	–7	–5,17	–	$10^{4.4}$	5.7
	850	Transverse bending	–	10^{-2}	454	255	21,6	–	10^4	6.8	271
			Compression	–	10^{-1}	465	186	11,5	–	$10^{5.7}$	8.5
Fiberboard	200–350	Transverse bending	–	$\frac{10^{1.8}}{10^{-0.5}}$	<u>400</u>	<u>230</u>	<u>20</u>	–	$\frac{10^{5.75}}{10^{3.02}}$	<u>8.3</u>	<u>304</u>
	850		–	$10^{5.85}$	182	–115	–9,16	–	$10^{1.35}$	14	191
	950		–	10^9	260	–588	–32	–	$10^{7.3}$	23.8	550
Phenol formaldehyde resin	–	Transverse bending	–	10^{-12}	1250	122	13,8	–	–	–	–

Notes: 1) strength and durability were calculated at a temperature of 288 K; 2) strength was calculated at $\tau = 105$ s, and durability – for chipboard and soft fiberboard at $\sigma = 7.6$ MPa, for hard fiberboard at $\sigma = 20$ MPa; 3) heat resistance was calculated at $\tau = 105$ s and $\sigma = 7.6$ (chipboard and soft fiberboard) or 20 MPa (hard fiberboard).

Table 3

Values of physical and empirical constants for transverse bending of plywood and laminate

Material	Load type	Temperature range, °C	Stress range, MPa	Physical constants				Performance			
				τ_m , s	T_m , K	U_0 , kJ/mol	γ , kJ/(MPa·mol)	τ , s	σ , MPa	T , K	
Plywood	FSF	Transverse bending	14–40	60–80	$10^{-0.88}$	369	633	7	$10^{7.5}$	69	–
			80–100	80–100	10^{-1}	303	3518	45			
			40–80	60–80	$10^{-0.4}$	431	486	5,6	–	–	–
				80–100	$10^{-1.1}$	400	790	8	–	–	–
Laminate	Transverse bending	20–80	110–130	$10^{-2.75}$	1010	209	1,4	$10^{13.3}$	106	–	
			140–150	$10^{-1.81}$	435	480	2,86				
Laminate	Transverse bending	< +60	–	$10^{-1.35}$	651	232	6,23	$10^{9.4}$	27	–	
		> +60	–	$10^{-2.7}$	410	707	17,85				

Notes: 1) strength and durability were calculated at a temperature of 288 K; 2) strength was calculated at $\tau = 10^5$ s, and durability – for laminate at $\sigma = 20$ MPa, for plywood at $\sigma = 60$ MPa.

This is confirmed by the tabular data: for chipboard with a density of 650 and 700 kg/m³, T_m has a value (540 and 571 K). For soft fiberboard and plywood, the pole temperature is slightly lower (384–430 K) [13], which is apparently due to the lower resin content in these materials. And for laminate, the T_m increases by 80 K, which is caused by the presence of other polymers used as an external protective film or binder. For solid fiberboard, as well as for wood, the limiting temperature is an empirical parameter that is in the low temperature range of 181–263 K [1].

The value of the activation energy U_0 indicates the breaking of chemical bonds [22] and for most wood composites (chipboard, laminate (up to 60 °C), fiberboard, plywood of FC grade) it is close to the value of U_0 of cellulose. The exception is chipboard with a density of 800 kg/m³, for which the activation energy corresponds to the value U_0 of phenol-formaldehyde resin [10].

Fiberboard is distinguished by its technological orientation, which most strongly affects τ_m^* , U_m^* and γ^* . Table 2 shows that for solid fiberboard the empirical constants U_0^* and γ^* have a negative value. Moreover, for fiberboard with a density of 850 kg/m³ T_m and U_0 are close to similar parameters of wood.

A number of materials have a complex character of destruction which in turn affects the value of the constants. So for a soft fiberboard at low stresses (layer-by-layer destruction) U_0 is close to the value of the maximum activation energy of the resin (see Table 2) [15], while at high stresses (monolithic destruction) it is equal to the maximum activation energy of cellulose. The values of the remaining constants confirm the change in the fracture mechanism of the soft fiberboard at certain boundary stresses [1, 21]. For laminate (Table 3) at temperatures up to +60 °C the value of the effective activation energy is close to U_0 for the destruction of cellulose [23], which indicates the decisive role in the destruction of the wood fiber base. With an increase in temperature, there is a sharp increase (2 times) of the activation energy. This fact is explained by the softening of the polymer binder, which in turn increases the deformability of the material [1].

For plywood of FK grade at high stresses (monolithic fracture) U_0 is close to the maximum activation energy of the resin (it is in these layers that cracks originate), while at low stresses (layer-by-layer destruction) it is equal to the maximum activation energy of cellulose, because there is a stepwise

destruction of individual layers. The values of the rest of the constants confirm the change in the mechanism of plywood destruction at certain boundary stresses. But for plywood of FSF grade, large values of the activation energy are characteristic, which is caused by the phenomenon of multiplicity [12, 13] – there is a destruction of not just one, but several bonds simultaneously.

On the example of chipboard, it can be seen that the values of the constants practically do not change when the density of the material changes. For chipboard with a density of 850 kg/m³, only γ significantly increases, which is apparently associated with a more homogeneous structure of the plastic caused by a decrease in voids [1, 21]. The dispersion of the filler, its size and quality, on the contrary, have a significant effect on the values of all physical constants. So τ_m and γ grow with decreasing chip homogeneity, and T_m falls. Apparently, as the dispersion of the filler increases, the fluctuation volume increases, which determines the size of the kinetic unit [5].

With an increase in the size of wood particles, pre-exponential τ_m decreases, which is also confirmed for polystyrene filled with granular glass. But with an increase in the amount of filler (a decrease in phenol-formaldehyde resin), its value increases, which is explained by the need for crack growth bypassing the filler particle [10]. The increase in the activation energy occurs abruptly at a high filler content.

When the direction of the force action changes, constant τ_m changes insignificantly. The limiting temperature T_m drops by 100 °C. The values of U_0 and γ change proportionally (by approximately 30 %). In this case, the value of the ultimate strength, equal to the ratio U_0/γ , is preserved and amounts to (14.7 ± 0.5) MPa [1, 24]. However, for denser materials with a change in the direction of force action, a slight change in the values of ultimate strength is observed. For chipboard with a density of 800 kg/m³, the ratio of ultimate strengths ($\sigma_{\perp}/\sigma_{\parallel}$) is 1.19, and for chipboard with a density of 850 kg/m³ it is 1.3. So, in both cases, the values of the maximum activation energy are close to the values of U_0 of cellulose, and the pole temperature is close to the decomposition temperature of phenol-formaldehyde resin [10].

Tables 2, 3 show that for all studied materials, when the load type changes, all or some of the constants change. This is most pronounced for chipboard with a density of 700 kg/m³. Under compression the value of the maximum activation energy more than doubles, which indicates the leading role of the deformation processes under this load type

[10]. This is also confirmed visually. In transverse bending, the samples fail in the middle of the span, and the separation process begins in the stretched zone. In the compressed zone of some fiberboard samples, even a thin unbroken film remains in the fracture plane. Under compression during testing, the sample is gradually flattened and, at the end, it is instantaneously destructed [1].

The leading role of the deformation processes is also manifested in the values of the remaining constants: γ increases by almost four times, τ_m increases by two orders of magnitude, the value of T_m is minimal and corresponds to the softening temperature of phenol-formaldehyde resin [10]. Large values of U_0 and γ are explained by the fact that the material deformation is associated with the displacement of segments relative to each other, which requires the simultaneous breaking of several tens of van der Waals bonds [12].

For chipboard with a density of 850 kg/m^3 , the value of U_0 during bending and compression is close to the activation energy of breaking chemical bonds. T_m also changes insignificantly with a change in the load type and coincides with the critical decomposition temperature of the resin. Consequently, for this grade of chipboard in compression, as well as in transverse bending, the leading process is destruction. In this case, the sharp flattening of the samples is prevented by the significantly lower concentration of voids filled with phenol-formaldehyde resin [21]. Changing the load type affects only the structural-mechanical constant γ . This is also confirmed by other materials: cement particle board, polystyrene, etc. [13, 25]

So, when the load type changes, three constants (U_0 , T_m , τ_m) remain constant, and only γ changes. However, this is not always the case with compression, since for highly deformable materials, the leading process is deformation, not destruction [1, 21], which leads to a significant increase in some constants.

For chipboard with a density of 800 kg/m^3 , a change in all constants is observed. This is caused by a change in the type of dependence.

The results obtained also show that the decisive factor in the destruction of most wood composites is wood filler, while the type of binder affects only the value of the limiting temperature. However, when the second filler is introduced into the composite, the value of most of the constants changes, which is caused by the formation of a complex multilevel structure.

The data obtained make it possible to predict the chipboard performance under different load types in a wide range of stresses, temperatures and operating

times. Tables 2 and 3 show the values of the main parameters of working capacity: strength, durability and heat resistance. Based on these results, the following conclusions can be drawn. The strength and durability of fiberboard is higher (1.75–2 times) than the strength of chipboard. However, this material is less heat resistant. In addition, the density of the plastic greatly affects the performance of fiberboard. Strength and durability also increase with its increase. Unlike fiberboard, the performance of chipboard is most influenced not by the density, but by the size and dispersion of the filler, as well as its quality. With an increase in the quality and homogeneity of the chips, the working capacity of the material increases by a factor of 1.05–1.2. The presence of the facing layer also leads to an increase in the strength and durability of chipboards [1], respectively, by 1.3 and 1.4 times.

When compressed, the strength of chipboard becomes 1.25 times higher than when bending, its durability is 1.42 times and heat resistance is 1.11 times higher. An exception is lined chipboard, for which the strength and durability during compression are 1.36 and 1.53 times less. This is apparently due to the fact that in compression, unlike bending, the lining does not affect the mechanical properties, since it affects only the top layer. Consequently, it is better to use hard chipboard in products working in compression, and lined ones in transverse bending [1].

Based on the above results, we will analyze the effect of the structure on the destruction mechanism of wood composites (Table 4).

The table shows that during destruction the classical form of dependence, i.e. a straight beam, is characteristic of composite materials with a chaotically located high-dispersion filler (**HDF**). With a decrease in the size of the filler, there are dependence transitions: first, to parallel straight lines (chipboards with small chips), then to the reverse beam (fiberboard). This behavior of composites, apparently, is associated with orientation in the process of pressing plates [26]. The dependence in the form of a backward beam is characteristic of oriented materials with a continuously reinforced fibrous structure, i.e. wood. However, when wood is modified, a transition of dependence from a reverse beam to a direct one is observed, which indicates an increase in the homogeneity of the material structure and a change in the mechanism of stress redistribution.

Materials with a laminated structure are characterized by a complex destruction mechanism. So, plywood works differently in the range of high and low stresses. When testing laminate, it was found that

Table 4

Effect of the structure on the dependence type of durability on inverse temperature for wood-based materials

Stress type	Fibrous					Impregnated (modified wood)	Laminated (plywood)	Laminated fibrous (laminate)	Laminated impregnated (laminated wood)
	Continuously Reinforced (wood)	Chipboard		Cement particle board	Fiberboard				
		with coarse chips	with fine chips						
Transverse bending failure	↗	↘	///	↗	↗	↘	Complex (splits into two straight beams) ↘↘	Complex (transition at temperatures above 60 °C) ↘	Complex (splits into two beams – reverse and direct) ↗↘
Deformation	↘	↘	↗	-	-	-	Complex (splits into two straight beams) ↘↘	-	Complex (splits into two beams – reverse and direct) ↗↘

its top layer, i.e. the polymer film starts working only at 60 °C. In this case, for both materials, the dependences take the form of a straight beam.

But for laminated wood, a change in the type of dependence is characteristic at elevated temperatures (> 40 °C). At the same time, at low temperatures, the decisive factor in destruction is the wood filler (the dependence is similar to the dependence of wood), and at high temperatures the adhesive layer also starts working (in this case, the form of the dependence is similar to the dependence obtained for modified wood).

When deformation takes place, wood behaves somewhat differently. So, its dependence of durability on stress and temperature takes the form of a straight beam. This suggests that orientation in the case of prolonged deformation does not affect the mechanism of material operation. The destruction and deformation behavior of wood-based boards is identical.

The size of the filler affects the strength of the composite. So, an increase in size leads to an increase in strength. The exception is fiberboard, the strength of which is higher than that of chipboard. This fact is precisely explained by the presence of a partial orientation in them. During modification, the strength of wood also increases, which is associated with the formation of an additional polymer frame inside the material.

This paper traces the effect of the number of layers on the durability and destruction mechanism of the composite using the example of FK plywood. For this purpose, using transverse bending, long-term tests were carried out in the mode of specified stresses and temperatures. The results are shown in Fig. 18.

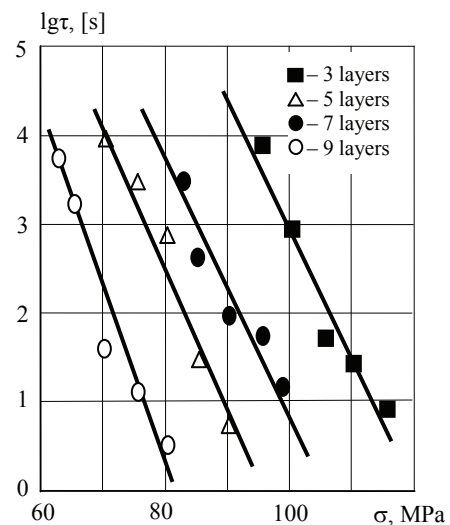


Fig. 18. Dependence of durability on stress during transverse bending for FK plywood of various layering

Physical constant values for transverse bending

Type of plywood	Number of layers	Temperature range, °C	Physical constants			
			τ_m, s	T_m, K	$U_0, kJ/mol$	$\gamma, kJ/(MPa \cdot mol)$
FK	3	20–60	$10^{-0.18}$	444	297.5	2.44
	5		$10^{-0.29}$	395	371	3.73

The figure shows that the dependence of durability on stress obtained for a different number of layers makes parallel lines, i.e. this factor does not affect the mechanism of plywood destruction itself, however, it affects its durability, the value of which decreases with an increase in the number of layers.

To test the assumption about the identical mechanism of destruction of plywood with different layering, additional tests were carried out at elevated temperatures. In this case, for three-layer and five-layer plywood, the dependences $\lg\tau-\sigma$ having the form of a straight beam and described by equation (1) were obtained. The constants included in this equation are presented in Table 5.

Table 5 shows that with an increase in the number of layers, the activation energy U_0 and the structural-mechanical constant γ increase, while the pole temperature T_m decreases. This behaviour of the material is apparently explained by an increase in the probability of defect formation with an increase in the number of layers, which in turn leads to a decrease in the homogeneity of the structure.

Conclusion

The results obtained for all wood materials considered above allow, without carrying out long-term tests, to correctly choose the type of dependence, the equation describing it and the values of the constants, which greatly simplifies the method of predicting their performance.

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