Durability prediction method for building materials

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Abstract. The prediction of durability can be approached from the perspective of the thermal fluctuation concept of fracture and deformation of solids. One of the drawbacks of this concept is the high labor intensity involved in determining the thermal fluctuation constants of the generalized Zhurkov equation, as well as the significant errors that may occur in their determination. The aim of this study is to develop methodologies that address and mitigate these shortcomings. The main scientific approaches employed are the hypothetical method and experimental studies (determining the durability of solids under non-destructive stress conditions). A description is provided of a developed methodology for determining thermal fluctuation constants based on a single straight line and one control point. The advantage of this approach is that it reduces the number of required experimental investigations by almost a factor of three. In the classical case, 15 points must be determined, whereas the proposed method requires only six. The main disadvantage of the method is the reduction in the accuracy of determining thermal fluctuation constants. Therefore, it is recommended for cases where approximate values are sufficient and minimal labor costs are desired. A description is also provided of the so-called "reference beam" method. This methodology is based on bringing the obtained fan-shaped family of straight lines converging at a single point (pole) to a selected reference family and determining thermal fluctuation constants using a system of conversion coefficients. Another proposed methodology makes it possible to determine the durability of solids without explicitly determining the thermal fluctuation constants. This method is based on a theoretically derived formula from the generalized Zhurkov equation for direct durability evaluation. The latter two methodologies increase the reliability of durability prediction for solids from the standpoint of the thermal fluctuation concept of fracture and deformation. The first of these methodologies significantly reduces the labor intensity of determining the thermal fluctuation constants of the generalized Zhurkov equation.

1. Introduction

The object of this study is the prediction of the durability of building materials and products within the framework of the thermal fluctuation concept of fracture and deformation of solids.

The prediction of building material properties, including durability, is among the most challenging issues in modern construction science. There are several approaches to predicting the durability of building materials [1–3]. In a number of studies, durability forecasting is considered from the standpoint of assessing the remaining service life [4–6], which serves as the basis for predicting the possible future service period. As a rule, this approach is used to estimate the durability of reinforced concrete structures. The initial components of construction materials have a strong influence on their durability [7–9]. One such approach is based on the thermal fluctuation nature of fracture and deformation of solids. This approach is considered within the framework of the thermal fluctuation concept of fracture and deformation, whose founder is rightfully considered to be Serafim Nikolaevich Zhurkov.

Zhurkov proposed that the fracture of a solid body should not be regarded as a critical event occurring when the stresses in the body reach a certain critical value, but rather as a probabilistic process that develops over time. In this context, mechanical loading is not the decisive factor in fracture; instead, thermal oscillations of kinetic particles are considered to be the primary driving force [10–12].

The thermal fluctuation concept of fracture and deformation of solids was further developed in the works of Solomon Borisovich Ratner, Georgy Mikhailovich Bartnev, Vadim Robertovich Regel, Valentin Evgenievich Gul, Engel Evgenievich Tomashevsky, Alexander Ilyich Slutsker, Viktor Petrovich Yartsev, and other researchers [13–15]. However, over the past two decades, the development of the thermal fluctuation concept of fracture and deformation of solids has practically come to a standstill. At the same time, with the advancement of science and technology, questions regarding the possibility and feasibility of applying the thermal fluctuation concept to the prediction of the durability of building materials and products have been increasingly raised [16, 17].

In the past decade, the Russian Federation has been facing increasingly significant challenges. One of the instruments for effectively addressing these challenges is the Fundamental Scientific Research Program for the Long-Term Period 2021–2030, adopted by the Government of the Russian Federation (Decree No. 3684-r of December 31, 2020). The adoption of this Program was based on the Federal Law "On the Russian Academy of Sciences, the Reorganization of State Academies of Sciences, and Amendments to Certain Legislative Acts of the Russian Federation."

One of the research tasks included in the construction sector research plan is to ensure "reliability, safety, and durability"[1]. To address the task of ensuring durability, it is essential to have at one's disposal tools and methodologies that allow for the accurate and adequate determination of the durability of building materials and products.

One of the main drawbacks of the thermal fluctuation concept of fracture and deformation of solids is the high labor intensity involved in determining the thermal fluctuation constants of the generalized Zhurkov equation, as well as the large errors in their determination. Experimental studies have shown that, when working with the same set of initial experimental data, two different specialists with the same level of expertise, applying the same methodology for determining the thermal fluctuation constants of the generalized Zhurkov equation, may obtain values that differ by up to 70 % [18]. This significant discrepancy is attributed to the use of the graph-analytical method for determining thermal fluctuation constants, combined with the need to work in semi-logarithmic coordinates of durability. Another drawback of the concept, also related to the high labor intensity of determining thermal fluctuation constants, stems from the fact that, according to the classical methodology, it is necessary to experimentally determine 15 data points of the durability–stress relationship (five points for each of three different temperatures), with each point being the result of testing no fewer than six specimens under identical conditions.

The outlined problems necessitate the development, within the framework of the thermal fluctuation concept of fracture and deformation of solids, of methodologies that are free from these shortcomings.

Thus, the aim of the present study is to advance methods for assessing the reliability and predicting the performance of building materials and products within the framework of the thermal fluctuation concept of fracture and deformation of solids.

To achieve this goal, it is necessary to develop a methodological basis for conducting the research, including the justification of the materials used, experimental procedures, and methods for processing the obtained experimental data. Furthermore, within the framework of the thermal fluctuation concept of fracture and deformation of solids and based on its further development, alternative methods for determining the strength and durability of solids should be developed. These methods should be characterized by increased reliability and reduced labor intensity in determining the thermal fluctuation constants of the generalized Zhurkov equation.

2. Methods

The primary scientific method used to obtain the initial data on the relationship between the durability of the material and the applied stresses and ambient temperature, necessary for the development of durability prediction methodologies within the framework of the thermal fluctuation concept of fracture and deformation, is experimental testing. The experiments were carried out on a six-position testing stand (Fig. 1), which is based on a metal frame (1) with support platforms (2). The support rods (3) serve as

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[1] Garant.ru. Rasporyazheniye Pravitelstva RF ot 31 dekabrya 2020 g. № 3684-r. Ob utverzhdenii Programmy fundamentalnykh nauchnykh issledovaniy v RF na dolgosrochnyy period (2021–2030 gg.) [Order of the Government of the Russian Federation of December 31, 2020 No. 3684-r. On approval of the Program of Fundamental Scientific Research in the Russian Federation for the long-term period (2021–2030)]. URL: https://www.garant.ru/products/ipo/prime/doc/400070256/ (date of application: 21.01.2026).

supports for the specimen (4), with the distance between them adjustable depending on the specimen length. To create the required stress in the specimens, a loading device (5) was used. Heating of the rod-type electric heaters (6), which provide the required temperature in the specimen loading zone, was achieved using a LATr 1M 220V-9A autotransformer. Temperature regulation was carried out with an EPV2-11A potentiometer, group XK, 0–300 °C, and monitored with a thermometer accurate to ±1 °C. To maintain the set temperature, a protective casing (7) was also used, which additionally serves to create a directed heat flow onto the specimens.

To eliminate the influence of mechanical vibrations during specimen fracture, a damping device was used – a container filled with sand, topped with a 20 mm thick rubber mat.
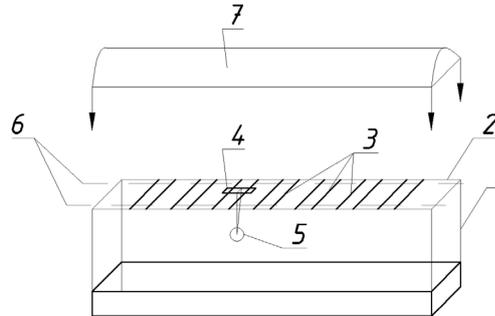
1 – metal frame; 2 – support platforms; 3 – support rods; 4 – specimen;
5 – load device; 6 – rod electric heaters; 7 – casing.

Figure 1. Schematic representation of the six-position stand for determination
of short-term transverse bending strength and durability.

Durability (time to reach the ultimate state under the action of non-critical stresses) was determined at three different temperatures, with the specimens conditioned at the corresponding temperature for at least 2 hours prior to testing. For each temperature, durability was measured at five stress levels ranging from 0.70 to 0.98 of the ultimate strength, which was determined on the same six-position testing stand using the standard procedure: calculation scheme – simply supported single-span beam, load – centrally applied concentrated force. The required load to achieve the specified stress in each specimen was calculated based on the condition of pure bending according to the single-span, simply supported beam model with a centrally applied concentrated load. Between 6 and 12 specimens were tested under identical conditions for each data point, and the obtained results were subjected to statistical processing.

Based on the obtained experimental data, methodologies for determining the durability of building materials within the framework of the thermal fluctuation concept of fracture and deformation of solids were developed and tested for adequacy.

The developed methodologies for determining the durability of building materials within the framework of the thermal fluctuation concept of fracture and deformation of solids are based on a previously proven hypothesis regarding the linearity of the variation of the angular coefficients of the temperature-dependent straight lines describing the relationship between the logarithm of durability and stress [19].

3. Results and Discussion

One of the thermal fluctuation constants of the generalized Zhurkov equation – specifically, the limiting temperature of solid-state existence – can be obtained outside the framework of the thermal fluctuation concept of fracture and deformation of solids by alternative methods. For example, it can be determined from a derivatogram, which in turn is the result of differential thermal analysis.

The remaining three thermal fluctuation constants of the generalized Zhurkov equation can be found mathematically by solving a certain system of equations based on an experimentally determined dependence of the logarithm of durability on voltage at a selected temperature and an experimentally determined control point (the dependence of the logarithm of durability on voltage) at a different temperature. Based on the proven hypothesis of the linearity of the change in the angular coefficients of the direct temperatures of the dependence of the logarithm of durability on voltage, while the line of the limiting temperature of the existence of a solid body is parallel to the stress axis of the graph of the dependence of the logarithm of durability on voltage and the presence of a limit temperature of the existence of a solid body determined in another way, a linear equation of the dependence of the change in the logarithm of durability on voltage at the temperature of the reference point is found. The ordinate of the intersection point of the equations of direct temperatures gives the value of the constant $\lg \tau_0$. The

remaining two constants are determined from solving a system of equations based on the generalized Zhurkov equation, in which two of the four constants are already known, as well as the values of the logarithm of durability under specific operating conditions (voltage and temperature).

Thus, when determining the thermal fluctuation constants of the generalized Zhurkov equation using the described method, the number of experiments is reduced by almost 3 times, which makes it possible to increase the number of studies per point. This technique can be used only if the material does not change its structure in the temperature range under consideration (the thermal fluctuation constants remain constant).

An analysis of the fundamental principles of the thermal fluctuation concept of fracture and deformation of solids, along with a comparative analysis of the experimentally obtained relationships between the logarithm of durability and both stress and ambient temperature, as well as the corresponding thermal fluctuation constants, suggests that the values of these constants depend on the coordinates of the pole point and on the rate of change of the slope coefficient of the temperature-dependent straight lines in the $\lg \tau - \sigma$ relationship. The variation of the constants as a function of changes in the pole point coordinates and the slope coefficient of the temperature lines should follow certain defined dependencies.

According to the classical principles of the thermal fluctuation concept of fracture and deformation of solids, which have been confirmed in practice, when the rate of change of the slope coefficient of the temperature-dependent lines is maintained, a shift of the pole point solely along the ordinate axis results in a linear change only in the constant $\lg \tau_0$ among the thermal fluctuation constants. Conversely, when the pole point is shifted solely along the abscissa axis, only the constant U_0, associated with the bond rupture energy, changes linearly.

To simplify calculations, and relying on the proven hypothesis of the linear variation of the slope coefficients of the temperature-dependent lines describing the relationship between the logarithm of durability and stress, one can refer to the change in the limiting temperature of solid-state existence, which will also exhibit a linear character. A change in the limiting temperature of solid-state existence leads to a linear change in the slope coefficients of the temperature lines. Considering that, in the classical case, the thermal fluctuation constants U_0 and γ are determined from a graph plotted in $U - \sigma$ coordinates, their variation is likewise linear, as has been experimentally confirmed.

The described dependencies make it possible to determine the thermal fluctuation constants of a material without reconstructing the obtained experimental graph in $\lg \tau - \sigma$ coordinates, as required in the classical methodology, but instead through manipulation of a reference bundle. This method has been named "Determination of Thermal Fluctuation Constants by the Reference Bundle Method." As the reference bundle, the set of lines shown in Fig. 2 is proposed, for which the thermal fluctuation constants have the values presented in Table 1. These values were obtained based on the experimentally determined constants of polyvinyl chloride plates tested under transverse bending: $\lg \tau_0$ = –2.34; γ = = 43.85 kJ/(mol·MPa); T_m = 437.95 K, U_0 = 313.85 kJ/mol.
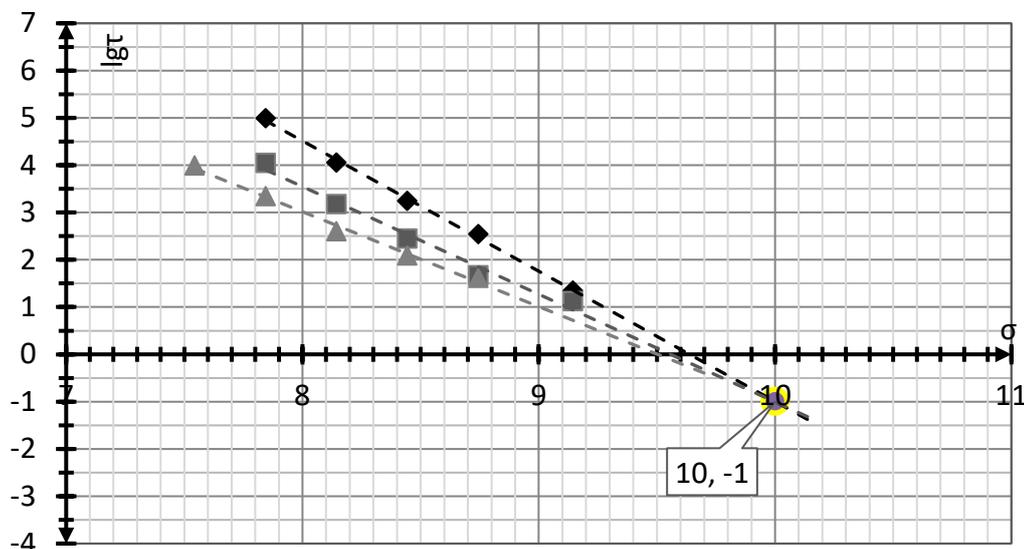

Figure 2. Reference beam.

Table 1. Thermal fluctuation constants of the reference beam.

γ, kJ/(mol·MPa)	U_0, kJ/mol	T_m, К	$\lg\tau_0$
50	500	500	−1

To find the thermal fluctuation constants using the reference beam method, the reference constants of Table 1 must be multiplied by the conversion coefficients (a system of coefficients). To do this, initially, based on the experimental dependences of the logarithm of durability on stresses and temperature, a family of fan-shaped straight lines is constructed in $\lg\tau - \sigma$ coordinates and the coordinates of the pole point are determined, as well as the value of the angular coefficient c^* of the equation of dependence of the angular coefficients of the forward temperatures of the graph in $\lg\tau - \sigma$ coordinates on the reverse temperature. Next, the conversion coefficients k_q and k_k are determined:

$$k_\sigma = \frac{\sigma}{\sigma_e}, \tag{1}$$

where σ – the point of the abscissa pole of the obtained graph of direct temperatures; σ_e – the points of the abscissa pole of the reference graph of direct temperatures;

$$k_k = \frac{c^*}{c_e^*}, \tag{2}$$

where c^* – the angular coefficient of the equations of dependence of the angular coefficients of the direct temperatures of the graph in coordinates $\lg - \sigma$ on the inverse temperature of the experimental graph; c_e^* – the angular coefficient of the equations of dependence of the angular coefficients of the direct temperatures of the graph in coordinates $\lg - \sigma$ on the inverse temperature of the reference graph.

For the accepted reference beam, $c_e^* = -2.619$.

The constant $\lg\tau_0$ is determined by the ordinate of the pole point of the obtained bundle of lines. The limiting temperature of solid-state existence is found from the linear relationship describing the variation of the slope coefficients of the equations.

The thermal fluctuation constant U_0 is determined by multiplying the reference constant $U_{0,e}$ by a system of coefficients k_σ and k_k:

$$U_0 = k_\sigma \cdot k_k \cdot U_{0,e} \tag{3}$$

The structural-mechanical constant γ_e is determined by multiplying the reference constant γ_e by the coefficient k_k:

$$\gamma = k_k \cdot \gamma_e. \tag{4}$$

Compared to the classical approach, the methodology is less labor-intensive and also allows one to avoid errors and inaccuracies that may arise during graphical constructions. The adequacy of the methodology has been verified on a range of building materials.

To derive a formula for determining the durability of solids without the need to determine the thermal fluctuation constants of the generalized Zhurkov equation, one can use the known mathematical relationships for calculating the thermal fluctuation constants. By introducing, for convenience, a set of notations and conditions, as presented in Fig. 3, it is possible to arrive at the following formulas for determining durability:

$$\tau = \tau_0 \cdot \exp\left[2.3 \cdot k \cdot 10^3 \cdot (\sigma_m - \sigma) \cdot \left(T^{-1} - T_m^{-1}\right)\right] \tag{5}$$

and

$$\lg \tau = \lg \tau_0 + 2.3 \cdot k \cdot 10^3 \cdot \left(\sigma_m - \sigma\right) \cdot \left(T^{-1} - T_m^{-1}\right). \tag{6}$$

In Fig. 3, the equation of the straight line corresponding to temperature T_1 is given by $\lg \tau = a_1\sigma + b_1$, and the equation of the straight line corresponding to temperature T_2 is given by $\lg \tau = a_2\sigma + b_2$. The notation of points is adopted as follows: $\lg \tau_n^m$, where n corresponds to the index of the selected stress level, and m corresponds to the index of the selected temperature.
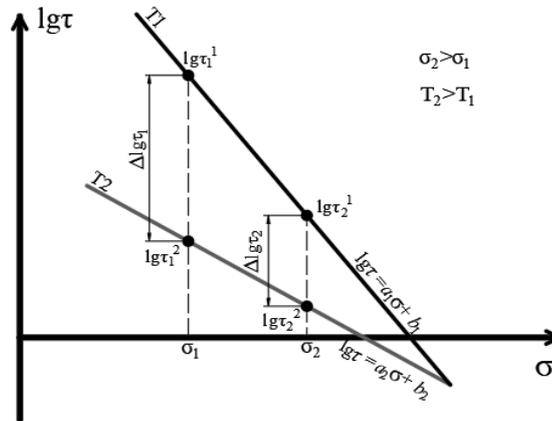
**Figure 3. Graph of the dependence of the decimal logarithm of durability
on voltage at a given temperature.**

The obtained formulas (5) and (6) make it possible to determine the durability of solids without calculating the thermal fluctuation constants γ and U_0, which in turn eliminates the need for additional graph reconstructions, thereby increasing the accuracy of the calculations.

The presented methods are original and were developed relatively recently; therefore, at the present time, no independent validations by other researchers have been reported. However, their application using experimental data obtained by other authors for wood-composite materials [20–22] and bitumen-based materials [23, 24] demonstrates a high degree of agreement with the results of determining thermal fluctuation constants by classical methods.

4. Conclusion

The proposed methodology for determining the thermal fluctuation constants of the generalized Zhurkov equation based on a single temperature line and one control point (a total of six points) makes it possible to reduce the labor intensity of their determination. However, its main drawback is the reduced accuracy of determining the thermal fluctuation constants. Therefore, it is recommended for cases where only approximate values are required with minimal labor costs. To simplify the determination of thermal fluctuation constants from experimentally obtained data, a computer program titled "Calculation of Thermal Fluctuation Constants of the Generalized Zhurkov Equation" was developed and officially registered.

The proposed reference bundle method improves the accuracy of determining the thermal fluctuation constants of the generalized Zhurkov equation by eliminating the need to reconstruct the original experimentally obtained graph in logarithm of time vs. stress coordinates into a graph in logarithm of time vs. inverse temperature coordinates, as required in the classical methodology. To automate the calculations, a computer program titled "Determination of Thermal Fluctuation Constants by the Reference Bundle Method" was developed and officially registered. In addition, Patent for Invention No. 2763483 was obtained for this method.

The proposed method for determining the durability of solids also improves the accuracy of durability assessment by completely eliminating the need for graph plotting and transitioning to a mathematical determination of durability. To automate the calculations, a computer program titled "Determination of the Durability of Solids" was developed and officially registered. In addition, Patent for Invention No. 2760177 was obtained for this method.

Further development of the thermal fluctuation concept of fracture and deformation of solids may proceed through the consideration of operating conditions as well as the prediction of durability from the standpoint of the loss of the material's thermophysical properties.

References

1. Suleymanov, A.M. Eksperimentalno-teoreticheskiye osnovy prognozirovaniya i povysheniya dolgovechnosti materialov myagkikh obolochek stroitelnogo naznacheniya [Experimental and theoretical foundations for predicting and increasing the durability of soft shell materials for construction purposes]: abstract of a dissertation for the degree of Doctor of Technical Sciences. Kazan State University of Architecture and Engineering. Kazan, 2006.

2. Shelikhov, N.S., Sagdiev, R.R., Timirgaliev, M.M. Design of a method for assessing the durability of building materials in aggressive environments. News of the Kazan State University of Architecture and Engineering. 2019. 4(50). Pp. 394–400.

3. Osipov, S.N., Zakharenko, A.V., Pozdnyakov, D.A. (2018) On Longevity of Solid Construction Materials. Science and Technique. 17 (4). Pp. 278–287. DOI: 10.21122/2227-1031-2018-17-4-278-287

4. Abdrahimova, N. Experimental and theoretical studies of plug joints reinforced concrete columns under transverse force. IOP Conference Series: Materials Science and Engineering. 890. Article no. 012053. DOI: 10.1088/1757-899X/890/1/012053

5. Temikeev, K., Abdykalykov, A., Zulpuev, A.M. Temir Bolot, Meshcheriakov, A.A. Estimation of the operation resource level of the load bearing structures of buildings and facilities during design and operation period. The Herald of Kyrgyz State Technical University. 2023. 65(1). Pp. 551–557. DOI: 10.56634/16948335.2023.1.551-557

6. Kashlev, Y.A., Maslyaev, S.A. The Rate of Fast Particles Leaving a Planar Channeled Regime in a Quasiclassical Approach. Inorganic Materials: Applied Research. 2020. 11(3). Pp. 514–519. DOI: 10.1134/S207511332003020X

7. Bescher, E., Vallens, K., Kim, J. Belitic calcium sulfoaluminate cement and its use in the United States. Cement and its Applications. 2020. 6. Pp. 90–95.

8. Pichugina, A.S., Vakhovskaya, R.V. Appliance of biomineralization in phosphogypsum roadbed compaction. Aktual'nye nauchnye issledovanija v sovremennom mire. 2021. 11-9(79). Pp. 25–31.

9. Rykunova, M.D. Svoystva tsementnogo testa i kamnya v prisutstvii glutarovogo aldegida [Properties of cement paste and stone in the presence of glutaric aldehyde]. Energosberezheniye i innovatsionnyye tekhnologii v toplivno-energeticheskom komplekse [Energy conservation and innovative technologies in the fuel and energy complex]. Industrial University of Tyumen. Tyumen, 2022. Pp. 50–53.

10. Korikov, D.V. Asymptotic Description of Fast Thermal Processes in Scalar Harmonic Lattices. Physics of the Solid State. 2020. 62(11). Pp. 2232–2241. DOI: 10.1134/S1063783420110177

11. Regel', V.R., Slutsker, A.I., Tomashevskiǐ, É.E. Reviews of Topical Problems: the Kinetic Nature of the Strength of Solids. Soviet Physics Uspekhi. 1972. 15(1). Pp. 45–65. DOI: 10.1070/PU1972v015n01ABEH004945

12. Tomashevskii, E.E., Zakrevskii, V.A., Novak, I.I., Korsukov, V.E., Regel, V.R., Pozdnyakov, O.F., Slutsker, A.I., Kuksenko, V.S. Kinetic micromechanics of polymer Fracture. International Journal of Fracture. 1975. 11(5). Pp. 803–815.

13. Yartsev, V.P., Voronkov, A.G. Influence of temperature on the range of energy of polymeric material activation under desctruction and strain. Bulletin of Volgograd State University of Architecture and Civil Engineering Series: Civil Engineering and Architecture. 2013. 31-2(50). Pp. 223–226.

14. Makarova, T.V., Potapov, Yu.B. Prognostication of Durability the Rubber Polymeric Concrete Based on Termofluctuation Theory of Destruction and Straining of Solid Bodies. Kompozitsionnye stroitelnye materialy i konstruktsii [Composite building materials and structures]. Voronezh State University of Architecture and Civil Engineering. Voronezh, 2014. Pp. 156–159.

15. Petrov, M.G. Investigation of the longevity of materials on the basis of the kinetic concept of fracture. Journal of Applied Mechanics and Technical Physics. 2021. 62(1). Pp. 145–156. DOI: 10.15372/PMTF20210118

16. Kovshov, A.G. Kinetic, Thermofluctuation Nature Friction Surfaces of Solid Friction during Wear. Izvestiya Samarskogo nauchnogo tsentra Rossiyskoy akademii nauk [News of the Samara Scientific Center of the Russian Academy of Sciences]. 2020. 22(3). Pp. 37–43. DOI: 10.37313/1990-5378-2020-22-3-37-43

17. Kienzler, D., Wan, Y., Erickson, S.D., Wu, J.J., Wilson, A.C., Wineland, D.J., Leibfried, D. Quantum Logic Spectroscopy with Ions in Thermal Motion. Physical Review X. 2020. 10(2). Article no. 021012. DOI: 10.1103/PhysRevX.10.021012

18. Gorokhov, T.I., Yerofeyev, A.V. Sravnitelnyy analiz pogreshnostey grafoanaliticheskogo i matematicheskogo metoda opredeleniya termofluktuatsionnykh konstantobobshchennogo uravneniya Zhurkova [Comparative Analysis of Errors in the Graphical-Analytical and Mathematical Method of Determining Thermal-Fluctuation Constants of the Generalized Zhurkov Equation]. Molodyye uchenyye – razvitiyu Natsionalnoy tekhnologicheskoy initsiativy (POISK) [Young scientists – for the development of the National Technology Initiative (POISK)]. 2020. 1. Pp. 142–144.

19. Yerofeyev, A.V., Gorokhov, T.I., Gorokhov, S.I. Gipoteza o lineynosti izmeneniya uglovykh koeffitsiyentov pryamykh temperatur zavisimosti logarifma dolgovechnosti ot napryazheniya [Hypothesis of the Linearity of Change in the Angular Coefficients of Direct Temperatures of the Dependence of the Logarithm of Durability on Voltage]. Aktualnyye voprosy arkhitektury i stroitelstva [Current issues in architecture and construction]. Ogarev Mordovia State University. Saransk, 2021. Pp. 291–295.

20. Pakhomova, E., Emelyanov, S., Yartsev, V., Danilov, V., Monastyrev, P. The Influence of Climatic Aging on the Performance of Wood-Based Panels. Civil Engineering Journal. 2023. 9(6). Pp. 1491–1508. DOI: 10.28991/cej-2023-09-06-015

21. Yarcev, V.P., Danilov, V.M. Influence of climatic aging on operating properties of fiberboard. Russian Journal of Building Construction and Architecture. 2023. 1(57). Pp. 66–76. – DOI: 10.36622/VSTU.2023.57.1.005

22. Mamontov, S., Mamontov, A., Monastyrev, P., Emelianov, S., Pahomova, E. Aging and Long-Term Mechanical Impact in the Durability of Wood Composites. Lecture Notes in Civil Engineering. 287. Modern Problems in Construction. Springer. Cham, 2023. Pp. 57–66. DOI: 10.1007/978-3-031-12703-8_7

23. Yarcev V. P., Danilov V. M. Thermal Fluctuation Regularities of the Fracture of Bituminous Composites. Russian Journal of Building Construction and Architecture. 2025. 1(77). Pp. 70–80. DOI: 10.36622/2541-7592.2025.77.1.007

24. Yarcev, V.P., Danilov, V.M., Suchkov, K.O. The Effect of Fillers on the Durability of Bitumen Composites. Stroitelnyye materialy, oborudovaniye, tekhnologii XXI veka [Construction materials, equipment, technologies of the 20th century]. 2025. 1(288). Pp. 62–65.

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