Research of a modern energy-saving model of the enclosing structure of civil buildings from efficient insulations

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Abstract. This article examines a modern energy-saving model of the enclosing structure of civil buildings made of effective insulation materials, which varies with different physics and mechanical properties, and complex studies of operational properties and calculations using the developed model of thermal insulation durability made it possible to obtain predictive values of the durability of various types of thermal insulation materials in the construction of wall fencing and make suggestions according to rational areas of application, incl. depending on the degree of capital of the building and the service life of the enclosing structures

1. Introduction

The energy efficiency of a building is the ability of an object and its engineering systems to provide a given level of thermal energy consumption to maintain optimal parameters of the microclimate of the premises, which is determined by a combination of many factors, including the level of thermal protection of enclosing structures. Practice shows that heat loss due to air infiltration through external fences constitutes a significant share (30-40%) in the balance of heat loss of a traditional multi-story building. Moreover, the main source; heat losses in the building are windows; the specific heat flux through double-layer glazing is approximately five times higher than that passing through the walls. But, given that the glazing area in an ordinary house is 15-20% of the wall area, we can assume that heat loss through the walls is maximum. Therefore, the issue of increasing the thermal protection of enclosing structures is one of the main concepts of an energy-efficient building [1].

The basic requirements for regulating the thermal protection of buildings are formulated in regulatory documents: *SNiP II -3-79** "Building Heat Engineering" (as amended No. 3 in 1995 and No. 4 in 1998) [2], *SNiP 02/23/2003* "Thermal protection of buildings" [3]. Etc.

Work in the field of substantiating the economic feasibility of carrying out capital repair procedures for buildings in order to increase their energy efficiency was carried out by *Yu.A.Vorobyova, T.A.Vasilyeva, A.V.Lunina, D.M.Sovpel* [7], *V.V.Plotnikov, A.S.Skantseva* [8], *A.A.Hamid., K.Farsäter, A.Wahlström, P.Wallentén* [9 (pp. 414–431)].

In the works of *Yu.A.Vorobyov, T.A.Vasiliev, A.V.Lunin, D.M.Sovpel* [7] assessed the physical wear and tear of typical residential buildings, taking into account their number of storeys and wall materials; a relationship was identified between a decrease in the thermal protection of enclosing structures made of various materials and the degree of wear of structures; recommendations were formulated regarding increasing the energy efficiency of buildings based on minimizing heat losses while ensuring comfortable microclimate parameters in the premises.

In the works of *V.V.Plotnikov, A.S.Skantsev* [8] identified the main reasons for changes in the appearance of brick, panel and monolithic frame houses during operation; the main factors influencing changes in the external appearance of multi-apartment residential buildings have been identified: short-sighted decisions of architects that do not take into account changes in the properties of building materials and structural elements during operation; insufficient thermal protection of buildings; violation of thermal insulation installation technology.

In the works of *A.A.Hamid, K.Farsäter, A.Wahlström, P.Wallentén* [9] reviewed publications on the renovation of apartment buildings in temperate climates; It was concluded that the issues of renovation of apartment buildings in temperate climates have been highly developed.

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Work in the field of substantiating the characteristics of wall (enclosing) structures and the building materials used within the framework of design solutions to increase the energy efficiency of buildings was studied by *A.E.Shvetsov, K.A.Pleshkova, S.I.Kryshov, I.S.Kurilyuk, O. A.Korol, A.E.Kiryudcheva, Shishkina V.V., Kramarenko A.V., Timoshkin T.V., Chebotarev V.S., Novikov M.V.* [10-15] *Chen Sh., Zhang G., Xia X., Setunge S., Shi L., Berger J., Mendes N.* [16, 17], *Calero M., Alameda-Hernandez E., Fernandez- Serrano M., Ronda A., Martin-Lara MA* [18], *Gori P., Guattari C., Evangelisti L., Asdrubali F* . [19], *Pavlov M.V., Karpov D.F., Berezina V.P., Gulak L.I., Zhabina A.A., Koveshnikova E.A., Aralov R.S., Starostin A.R., Koloskov V.V., Kutiev A.V., Stepanov G.A., Musorina T.A.* [20-23], *Tarasenko V.N., Denisov Yu.V.* [24], *Schiavoni S., D'Alessandro F., Bianchi F., Asdrubali F.* [25], *Kumar D., Alam M., Zou PXW, Sanjayan JG, Memon RA* [26], *Vasilyeva I.L., Nemova D.V. [27].*

In the works of *Shvetsov A.E., Pleshkova K.A., Kryshov S.I., Kurilyuk I.S., Korol O.A., Kiryudcheva A.E., Shishkina V.V., Kramarenko A.V., Timoshkin T.V., Chebotarev V.S., Novikov M.V.* [10-15] studied the properties of building envelope materials that directly affect the energy efficiency of a building (including thermal protection indicators), its durability, etc.; a conclusion was made about the advisability of choosing a façade system based on the amount of financial costs and technical requirements of the facility under construction; An economic justification is given for the impossibility of abandoning traditional energy-efficient materials in favor of innovative ones in modern conditions.

In *Chen's WorksSh., ZhangG., XiaX., Setunge S., ShiL., BergerJ., MendesN.* [16,17] certain factors that influence the energy efficiency of buildings and which must be taken into account when developing design solutions in the field of increasing it: design features of buildings, features of the equipment and technologies used, as well as features of the operation process (determined by the behavior of personnel or residents)

In the works of *CaleroM., Alameda – Hernandez E., Fernandez - SerranoM., RondaA., Martin - LaraM. A.* [18] proposed measures to reduce energy consumption during the operation of thermal systems of residential buildings, including through the installation of solar panels on the facades of existing buildings.

In the works *of GoriP., GuattariC., EvangelistiL., AsdrubaliF.* [19] defined criteria for assessing the effectiveness of implementing design solutions to increase the energy efficiency of multilayer wall structures, including energy savings in buildings by optimizing the insulating properties of external walls.

In the works *Pavlov M.V., Karpov D.F., Berezina V.P., Gulak L.I., Zhabin A.A., Koveshnikova E.A., Aralov R.S., Starostin A.R., Koloskov V.V., Kutiev A.V., Stepanov G.A. Musorina T.A.* [20-23] carried out a detailed analysis of modern traditional and innovative thermal insulation materials in terms of the main thermal characteristics, scope of application, comparative advantages and disadvantages of corresponding design solutions; and also a conclusion was made about a relatively large range of values for the thickness and cost of material samples with a relatively small range of thermal characteristics.

In the works of *Tarasenko V.N., Denisov Yu.V.* [24] analyzed the domestic and foreign markets for thermal insulation materials; and also identified factors for the further development of the Russian market of thermal insulation materials: increasing interest of construction organizations in energy-efficient engineering solutions, monopolization of the market of thermal insulation materials, development of state energy saving programs, problems of low-quality materials.

In the works of *Schiavoni S., D'Alessandro F., Bianchi F., Asdrubali F.* [25] a review and comparative analysis of building insulating materials was performed in terms of thermal characteristics, acoustic properties, fire resistance and vapor permeability; and it was also concluded that the most promising materials are vacuum and gas-filled insulating panels, which are characterized by the lowest thermal conductivity values, but their widespread implementation is not yet available due to their high cost.

D. , *Alam M., Zou PXW, Sanjayan JG, Memon RA* [26] analyzed the thermal, hygroscopic, acoustic and other properties, as well as fire resistance and cost of building thermal insulation materials; it was concluded that wall (enclosing) structures of buildings with relatively low and high thermal resistance are more preferable in terms of profitability for regions with a predominance of low and high temperatures, respectively; It was concluded that wall (enclosing) structures with relatively high thermal insulation rates (as part of the so-called "hermetic" houses) cause an increase in the likelihood of overheating of the corresponding premises and their peak need for cooling in the summer.

In the works of *Vasiliev I.L., Nemov D.V.* [28] carried out a review and comparative analysis of new generation energy-efficient materials used in construction: liquid thermal insulation, airgel and vacuum thermal insulation panels; The advantages of these materials in comparison with traditional insulation materials have been determined - very low thermal conductivity coefficient, high environmental friendliness, low weight - and the main disadvantage is the relatively high cost.

Based on the data, the following conclusions were made:

- a significant part of scientific works of a review and methodological nature are based on the implementation and analysis of the results of experimental studies in the field of identifying and assessing the relationships between the technical and economic characteristics of building materials used in the construction of wall (enclosing) structures and the indicators of heat and moisture transfer processes that directly affect energy efficiency of corresponding design solutions; at the same time, the results of most relevant studies are practical recommendations regarding the formation

of design solutions in the field of increasing the energy efficiency of wall (enclosing) structures without a description of any tools that provide a numerical solution to the relevant applied problems;
- the vast majority of works from the point of view of the field of study are fragmentary in nature due to the lack of simultaneous consideration of the features of heat and moisture transfer processes within the framework of wall structures, regulatory requirements regarding the thermal characteristics of structures and the economic feasibility of corresponding design solutions.

2. Methods

Experience in the production, research and use of thermal insulation materials in structural thermal protection systems for buildings makes it possible to identify the most effective types of building thermal insulation in the general range of these products and outline the main ways to improve them in the direction of increasing operational properties and durability associated with the transition to a high-quality raw material base and improving processing technology , with a decrease in material consumption and an increase in thermal properties due to the targeted regulation of the structural parameters of gas-filled systems while simultaneously ensuring their fire and environmental safety, as well as minimizing energy costs both in the production and operation of these materials 1.
Thus, for thermal protection systems using mineral gas-filled insulation, the priorities are materials with a finely dispersed structure based on superfine fibers of high hydrolytic resistance, obtained from natural minerals with a high acidity modulus and high-quality phenolic binder; basalt plastic compositions based on amonosilicate mineral binders, processed at normal temperature and pressure 30.
The increased rigidity of gas-filled organomineral materials predetermined, first of all, their use in the construction of self-supporting multilayer walls, insulation of light coatings based on thin sheets of metal, asbestos cement and other cement-fiber materials in order to ensure the stability of these elements under operational loads. In particular, perlitophenol foam composites are very effective in the manufacture of lightweight multilayer insulated panels based on prefabricated profiled aluminum and steel sheets for industrial and public buildings. When using polystyrene cement insulation, its increased density and fragility should be taken into account. Therefore, options were found for the use of blocks made of expanded clay polystyrene concrete, characterized by increased thermal insulation characteristics when constructing multilayer walls 1.
This ensures increased durability of fences compared to polymer insulation.
Currently, in almost all developed countries, the main effective thermal insulation materials are products based on mineral and glass fiber. In the USA their volume is 85-90%, in Russia about 60%. Modern technology makes it possible to obtain products from mineral and glass fibers of specified thickness and length in a wide range.
In this regard, to determine the optimal parameters of fibers, studies were carried out on the content of components, their properties and layout, which affect the structure of the material and, basically, predetermine the macroscopic parameters of thermal insulation products. Materials with a fibrous structure contain three components: fiber, air and a binder. For modern effective materials with a density of up to 100 kg/m ^{3,} the volumetric content of these components is, respectively, m_1 <0.04, t_2 <0.95-0.96, t_3 <0.005.
Value $t_2$characterizes the porosity of products. The apparent density or volumetric mass of products is found from the expression:

$$\gamma_0 = m_1\rho_1 = (1 - m_2)\rho_в$$

$\rho_в$true fiber density. Typically $\rho_в$= 2500-2800 kg/ m^2 .
The mass of material consumed per 1 m of insulated surface is calculated using the formula:

$$M = \gamma_0\delta = \gamma_0 R_0 \lambda$$

This value mainly determines the cost of thermal insulation of 1 m^3 of a structure: the lower the apparent density and thermal conductivity of the material, the lower the cost of thermal insulation.
To estimate the thermal conductivity of materials of various structures, the following expression was found:

$$\lambda = (1 - K)[(1 - m_2)\lambda_1 + m_2\lambda_1] + K\frac{\lambda_1\lambda_2}{(1 - m_2)\lambda_2 + m_2\lambda_1}$$

where: $\lambda_1$thermal conductivity of the fiber;
$\lambda_2$thermal conductivity of air;
K is a structural coefficient characterizing the structure of the material.
Based on the analysis for fibrous structures (the direction of heat flow is perpendicular to the fibers), a simpler expression was obtained:

$$\lambda \approx 0.25\lambda_1\left[1 - m_2(1 - v) + 3\left(\frac{v}{m_2}\right)\right],$$

where: v is the ratio of the thermal conductivity of air to the thermal conductivity of the frame (fiber).

The values of λ_1, λ_2 and v vary significantly depending on t_2 and operating conditions (temperature, humidity, conditions of ventilation of thermal insulation). For $m_2 > 0.9$, this dependence can be expressed by the formulas (Figure 1):

$$\lambda_2 = 0.022 + 40d \cdot \frac{m_2}{1-m_2},$$

where: *d* fiber diameter.

$$v = \frac{0.22 + 40d \cdot \frac{m_2}{1-m_2}}{v}$$

It is advisable to introduce this amendment into the formula when the apparent density of thermal insulation materials is less than 80 kg/m (light slabs and mats).

The inherent nature of the change in thermal conductivity from the porosity of the fiber diameter and temperature at d = 3-5 μm is shown in Figure 1. From the data presented it is clear that for ultra-light fibrous materials the influence of porosity on thermal conductivity begins to have a significant effect at t_2 <0.95 *and* t = 30-100°C, since in this case the pore sizes increase and the influence of air convection in the pores increases. The influence of humidity on the thermal conductivity of porous fiber materials is significant. According to 3134, moistening materials with a fibrous structure with a density of 150 kg/m3 by 1% (by volume) leads to an increase in thermal conductivity by 8%.

The hygroscopicity of glass fiber materials is low: individual fiber 0.2%, glass fiber fabric 3-4%, which is significantly less than the hygroscopicity of cotton (8%), wool (6%), peat board grade 200 (28%), fiberboard grade 300 (30.7).

The total surface area of the fibers can be easily determined from the formula:

$$S = 2\pi r l,$$

Where: r average fiber radius; l overall length.

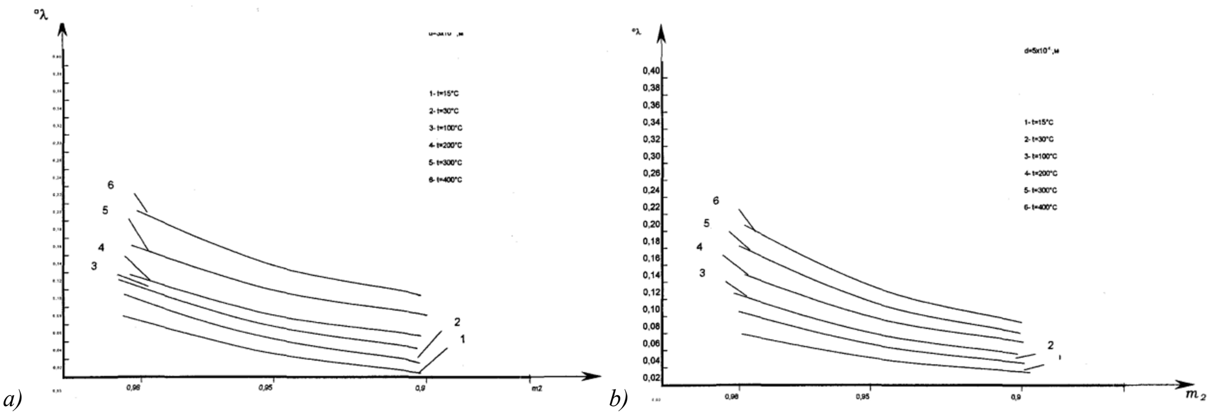

Fig. 1. The nature of the change in the thermal conductivity of a fibrous material depending on its porosity, fiber diameter and temperature

At the same time $\frac{\pi r^2}{\gamma} = \gamma_0$, therefore, the specific surface area per 1 m ^{3} of the product is equal $S = \frac{2\gamma_0}{r\rho}$.

in accordance with the classification of P.A.Rebinder 35, the following types of communication of moisture with the surface of the material are distinguished: chemical, physicochemical (adsorption) and physicomechanical (capillary).

In the case under consideration, chemically bound water can be formed due to the hydration of glass. Adsorption-bound water, according to the analysis of the Brunauer-Emet Teller equation (BET equation), forms a layer on the surface of the fibers with a thickness of about 10^{-7} m. Hence, when $r = 5 \cdot 10^{-6}$ m, water absorption due to adsorption is insignificant, on the order of 0.001-0.002%.

Capillary moisture can form only at the points of contact between fibers, which explains the relatively low hygroscopicity of such materials and the small change in their thermal conductivity in an atmosphere with high humidity. But if the design does not provide protection from moisture, hygroscopicity increases in proportion to the increase in the number of contacts.

The order of the number of contacts *n* between the fibers of the material per 1 m^3 of the product can be determined from the expression:

$$n = \left(\frac{\gamma_0}{\pi\rho}\right)^2 \frac{1}{r^3}$$

 https://doi.org/10.1051/e3sconf/202449702009

Figure 2 shows the dependence of n on the thickness of the fibers (2.5 µm and 10 µm) and the density of the material 20, 50, 100 and 150 kg/m.

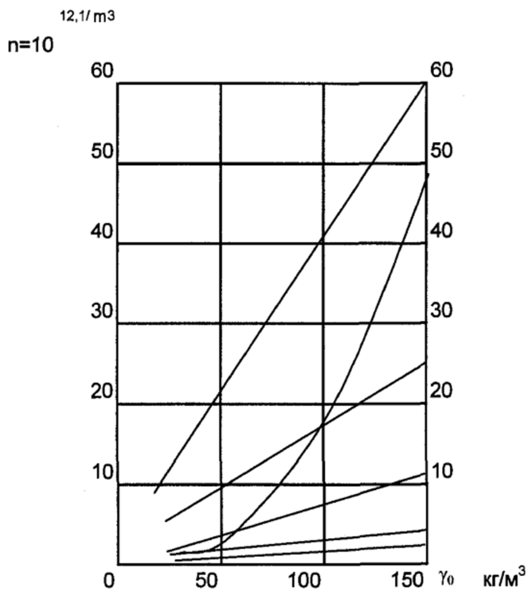

Fig. 2. Dependence of the number of contacts on the density and diameter of the fibers 36: 1.1' at r = 2* 10^{-6} ; 2.2' at r = 5*10 $^{-5}$; 3.3' at g = 10*10 $^{-6}$ m

A sharp increase in the specific surface area and the number of contacts with an increase in the density of products and a decrease in the radius of the fiber cannot but affect the behavior of the fibers when moistened. Thus, lightweight mats made of super-thin fibers of small diameters significantly change their volume under the action of capillary forces (they become denser) and their thermal conductivity increases. After drying, the volume is not completely restored, therefore moisture from the mats must be removed by ventilating the structure of the layered fence. It should be noted that products made from mineral fibers are generally quick-drying 37.

For porous fiber materials, the structural parameters are expressed by the totality of the stochastic distribution of fibers (solid phase) over the volume of the product and the sizes of the gas-structural elements formed by them, which in turn depend on the diameter of the fibers and the degree of their compaction. Accordingly, the intensity of heat and mass transfer processes in porous fiber materials will also be determined by the diameter of the fibers and the density of the product. An illustration is the obtained dependence of the thermal conductivity coefficient on the diameter of basalt fibers at a product density of 100 kg/m, presented in Table. 1 37,38, 39.

3. Results and Discussion

Experience shows that most thermal insulation materials retain their original thermophysical properties for a relatively short time for structures, not exceeding 25-26 years 34.

The thermal conductivity of thermal insulation materials increases with increasing temperature (Fig. 2). The thermal conductivity of mineral wool products depends on the average layer temperature t_{cp} and is determined by formulas like:

$$\lambda = \lambda_0 + bt_{\text{cp}} \quad (1)$$

where the coefficient values*b* are given in table 1.

Column 4 of Table 2 shows the approximate values of the thermal conductivity coefficient accepted for calculations of low-temperature thermal insulation at $t_{c\,p}$ = -60°C, +20°C based on the results of studies of the patterns of heat and moisture exchange of thermal insulation and the developed engineering methodology for calculating the thermal conductivity of moistened thermal insulation 46.

However, in the temperature range from 0 to 50 C, the influence of elevated temperatures is inferior to the influence of humidity. The practice of operating multi-storey refrigerators shows that with insufficient vapor barrier, even the thermal insulation layer can be moistened in 20-27 years to 154 - 177% by weight, which leads to an unacceptable increase in thermal conductivity and a decrease in the heat-protective properties of the fence. Addiction Research thermal conductivity from the moisture content of thermal insulation made of mineral wool with a density of 200 kg/m showed that with such moisture the thermal conductivity coefficient of the insulation increases 7 times 34.

Table 1. Dependence of thermal conductivity of mineral wool thermal insulationfrom t_{cp} and w

Product brand		Average density, kg/m ^{3}	Dependence of thermal conductivity on the average positive temperature t_{cp}	Calculated thermal conductivity taking into account humidity 46
Mineral wool products with corrugated structure stamps 75 100		<100 <130	0.045+0.00021 t_{cp} 0.049+0.0002 t_{cp}	
Plates with synthetic binder	Stamps 50 75 125 175	<75 115 150 210	0.04+0.00029 t_{cp} 0.043+0.00022 t_{cp} 0.044+0.00021 t_{cp} 0.052+0.0002 t_{cp}	0.054 0.057 0.06
Phenolic bonded slabs50 80 90		50 80 100	0.04+0.00022 t_{cp} 0.042+0.00023 t_{cp} 0.043+0.00019 t_{cp}	-
Mats and cotton wool on BSTV		50-100	0.033+0.00014 t_{cp}	0.044
Mats made of vertically layered mineral -wool		115-130	0.044+0.00031 t_{cp}	
Stitched mats	stamps 100 125	130 160	0.045+0.00021 t_{cp} 0.049+0.0002 t_{cp}	0.059
Fiberglass mats with synthetic bond		60 80	0.04+0.0003 t_{cp} 0.042+0.00028 t_{cp}	0.048
Foam plastic FRP-1	stamps 75 100	65-85 86-110	0.04+0.00023 t_{cp} 0.043+0.00019 t_{cp}	0.051 0.057
Polyurethane foam PPU-331/ZM		40-60 60-80	0.035 t_{cp}	0.036 0.037
Expanded polystyrene plates stamps15 25 35, 50		15 25 35.50	0.038 t_{cp}	0.048 0.044 0.042

Table 2. Dependence of the thermal conductivity coefficient on the diameter of basalt fibers at a product density of 100 kg/m

Average fiber diameter, µm	Thermal conductivity coefficient, W/(m.K) at average temperature, °C		
	50	300	500
0.6	0.0313	0.0685	0.0977
0.75	0.0322	0.0686	0.0983
1.2	0.0372	0.0779	0.1105
6.0	0.0472	0.1035	0.1483
10.3	0.0494	0.1192	0.1750
15.0	0.0502	0.1244	0.1838
18.0	0.0529	0.1296	0.1878

The given results are quite natural and are in full accordance with the physical essence of the ongoing processes. Low values of the thermal conductivity coefficient of products with fibers, the diameter of which is in the range of 0.6-1.2 microns, are due to a highly developed spatial structure formed by a huge number of tiny pores that provide great resistance to radiant heat transfer and convection air flows. On the contrary, coarser fibers with a diameter of more than 5 microns form a structure with large pores, in which convection processes already play a significantly noticeable role, in addition, the contribution of the thermal conductivity of the solid phase (directly mineral fibers) also increases. The mechanism of connection between thermal conductivity and the density of basalt fiber products is also similar, which is confirmed by the results in Table 2.

The presence of an optimum in the change in thermal conductivity, corresponding to the density range of 75-100 kg/m, indicates the predominant influence on the thermal conductivity coefficient of convection and heat transfer processes, which are easily realized in large-porous structures with large air inclusions that form fibrous materials with a density below 50 kg/m m. As the density increases, the mass of thermally conductive mineral components increases, leading to an increase in the thermal conductivity of the product as a whole.

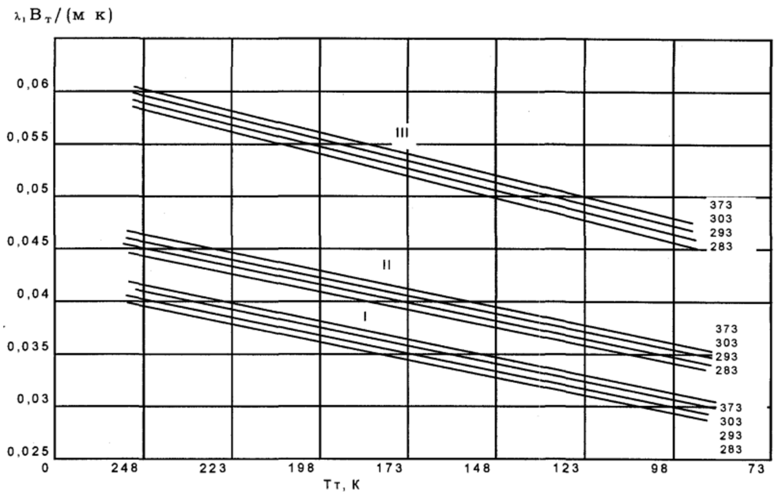

Fig. 3. Dependence of thermal conductivity on temperature: I foam plastics, II mineral and glass wool, III rigid mini-slab with bitumen bond

To verify the λ of basalt wool, an experiment was conducted to determine certain physical quantities using XND -2-3030 C «flat plate thermal conductivity instrument» in table 3 and figure 4.

Table 3. "Name of material to be tested" Test report of thermal conductivity of materials

Index	Name	Content	Index	Name	Content
1	Sa Name	Name of material to be tested	17	Model	300×300×40.0[mm]
2	Unit	XXX Testing company	18	ReportDate	2023-10-10 17:15:38
3	Factory	XXX Thermal insulation material factory	19	Area	0.0225[㎡]
4	Grade	XXX Sample grade	20	thickness	40.0[mm]
5	Brand	XXX Brand	21	ProtectT	35.6[℃]
6	Type	XXX Inspection category	22	HotT	36.6[℃]
7	Sa Nums	X	23	ColdT	14.9[℃]
8	Address		24	Duration	0[S]
9	Base	Sampling base	25	Test Date	2023-10-10 11:31:57
10	Sa Date		26	mode	Double specimen structure
11	Name	Sample sending person	27	standard	Thermal insulation-Determination of steady-state thermal resistance and related properties-Guarded hot plate apparatus
12	Fac date		28	Number	GB/T 10294-2008
13	Inspection	Thermal conductivity test	29		Result
14	examine	Name of reviewer	30	TCD	0.055729[W/(m K)]
15	inspection	Name of testing personnel	31	TRC	0.717757[m^2·K/W]
16	Approval	Name of the person who approved the test	32	Is it qualified	

The developed open-porous structure of gas-filled fibrous materials determines their fairly high-water sorption capacity. The kinetics of moisture and water absorption of samples of basalt fiber insulation with a density of 150-200 kg/m^2, obtained by mechanical mixing of hydromass using an inorganic binder, is presented in Figures 5 and 6.

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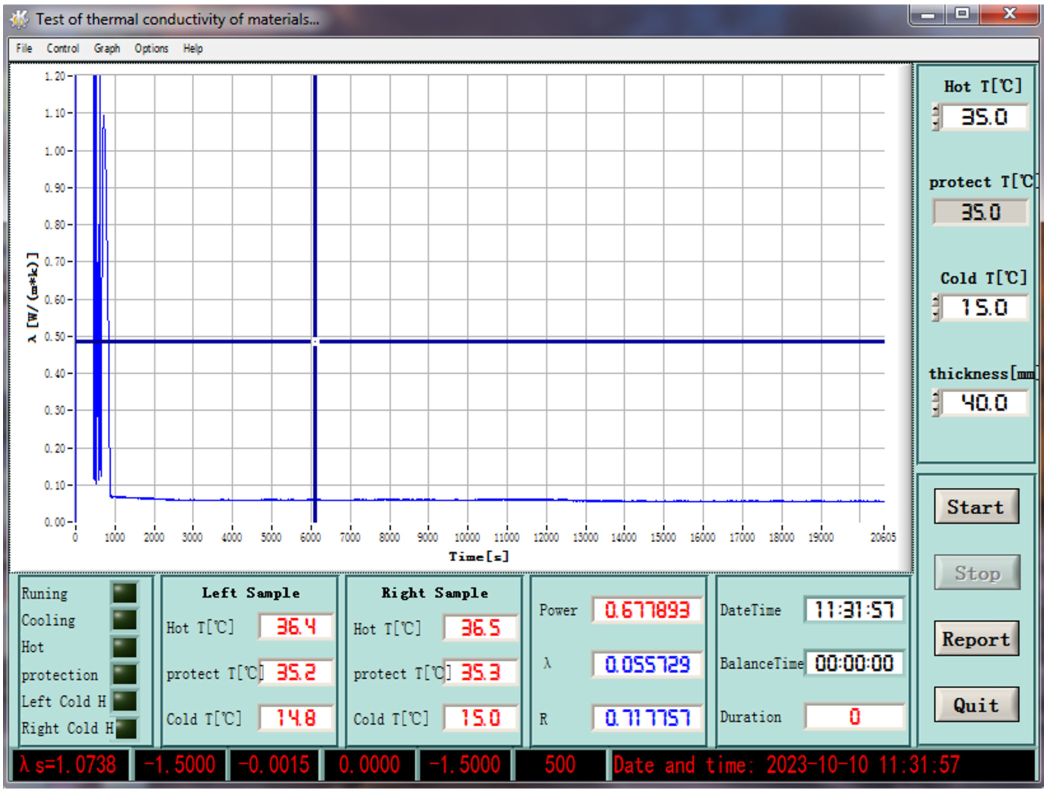

Figure 4. Test report of thermal conductivity of materials

Table 4. Dependence of thermal conductivity on the density of products.

Product density, kg/m ^{3}	Thermal conductivity coefficient, W/(m.K) at average temperature, °C		
	0	50	300
20	0.0337	0.0505	0.1342
50	0.0302	0.0383	0.0787
75	0.0279	0.0358	0.0750
100	0.0291	0.0372	0.0779
150	0.0302	0.0387	0.0812
200	0.0326	0.0416	0.08699

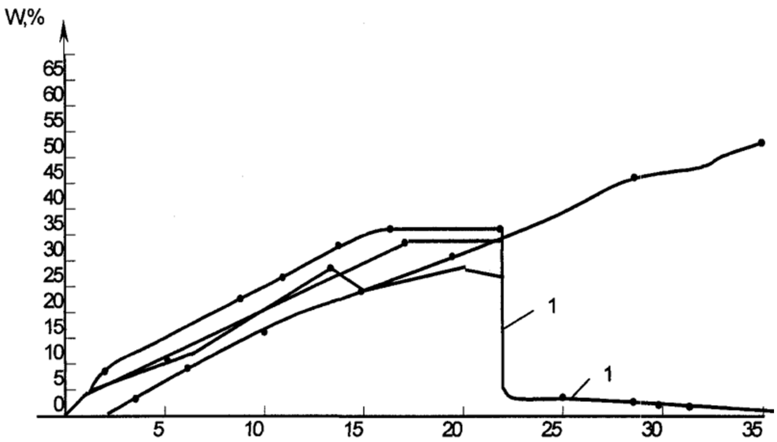

Figure 5. Kinetics of moisture absorption of basalt fiber insulation (1)

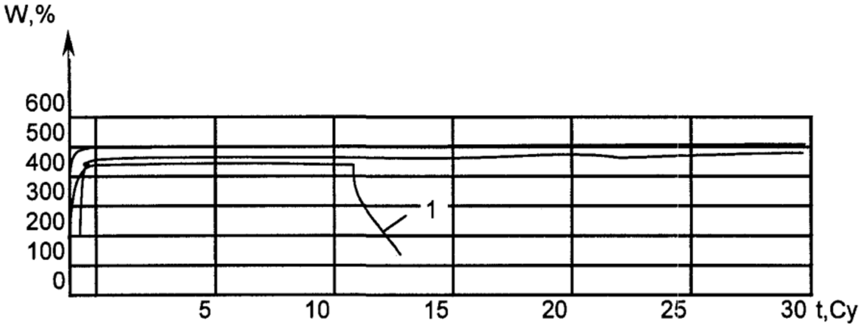

Fig. 6. Kinetics of moisture removal from basalt fiber insulation (1)

Two circumstances are noteworthy: firstly, the rather slow absorption of water vapor, which does not become saturated even after 60 days at a high rate of water absorption under conditions of complete immersion of samples in water and, secondly, extremely rapid removal (during the first days) both moisture and water from the moistened material when it dries under normal temperature and humidity conditions.

The influence of humidity factors is manifested not only in the sorption moistening of the material, but also in the change in its mechanical strength due to the chemical interaction of water and the mineral matrix. The results of mechanical tests of slab samples in their plane made of basalt fiber material are given in Table 5. Pre-wetting for 15-20 days, and then drying to an equilibrium moisture state, revealed not only a slight decrease in strength (no more than 5%), but even a slight increase, in all likelihood, due to changes in the mechanical characteristics of the binder, but not the fibers 40.

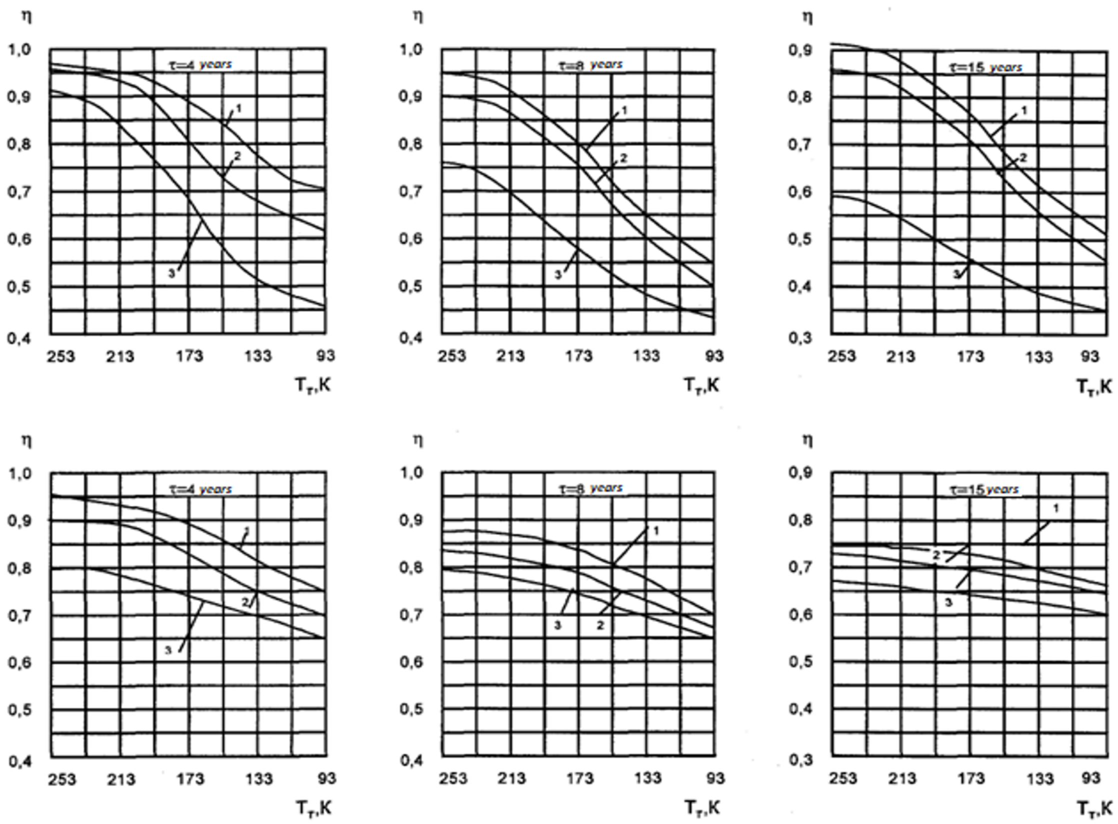

Fig. 7. Dependence of coefficient μ on service life and vapor permeation resistance *R n and* for open-porous materials, *b* for closed-porous materials.

Based on the foregoing, we can conclude that in real operating conditions, which provide for mandatory protection of thermal insulation from direct moisture exposure by structural elements, the economic parameters of basalt fiber insulation are ensured.

Table 5. Long-term strength of basalt fiber insulation

Density, kg/m 3	Duration of exposure, days/type of exposure	Compression, MPa	Tensile, MPa
175	15/C*	0.175'70.95	0.06/1.5
175	20/C	0.194/1.05	0.045/1.1
190	20/C	0.22/1.1	0.13/1.3
170	20/V	0.2/1.12	0.044/1.1

Note: *With sorption humidification; In moisture absorption;
** The numerator gives an indicator of the strength of moistened samples, the denominator is the ratio of this indicator to the indicator of a sample not subjected to water-moisture exposure.

At an operating temperature of 20°C (253°K), the coefficient η for open-cell thermal insulation materials with minimal vapor barrier protection from moisture during operation from 4 to 15 years drops sharply from 0,92 to 0,58 or by 42%; for closed-cell materials it decreases by more than smoothly from 0,82 to 0.77 or by 23%. When the vapor permeation resistance increases to 14,4 (0.12 mm thick polyethylene film) for open-cell thermal insulation, the drop gradient becomes similar to closed-cell material: from 0,97 to 0,86 or 14% and from 0,92 to 0,8 or 20% respectively. A further increase in vapor permeation resistance by 1.7 times (isol or aluminum foil) leads to a decrease in η over 15 years for an open-porous material by only 6%, for a closed-porous material by 18%. Accordingly, the thermal conductivity of the heat-insulating layer made of these materials increases. Comparison of these data with the values of column 4 of table. 5shows that for unprotected thermal insulation, the increase in thermal conductivity over 15 years is: mineral wool 35%, mats 40%

4. Conclusions

1. Analyzing thermal conductivity data using different methods, we can conclude that during operation in a fence under the complex cyclic influence of temperature and humidity, the thermophysical characteristics of thermal insulation materials increase: to a greater extent for open-cell materials, to a lesser extent for closed-cell materials.
2. As in polymer mechanics, the coefficient of long-term operating conditions in a structure depends on the operating time, humidity and resistance of the material, determined by the characteristics of the structure, and varies according to various calculated and experimental data for a service life of 15 years from 1.05 to 1.23; 30 years 1.29 1.32; 50 years from 1.63 to 2.3, including:
   PSB 1.3 1.63 times;
   FRP up to 2.3 times;
   Mineral wool 1.44 ÷ 2 times.
3. Thus, comprehensive studies of operational properties and calculations using the developed thermal insulation durability model made it possible to obtain predictive values for the durability of various types of thermal insulation materials in the construction of wall enclosures and make proposals for rational areas of application, incl. depending on the degree of capital of the building and the service life of the enclosing structures:
   polystyrene and polyurethane foams and rigid and semi-rigid mineral wool boards are recommended for three-layer panels and two-layer curtain walls, provided that proper para-insulation is installed;
   It is advisable to use mineral wool and glass wool for ventilated structures with facing slabs or shells;
   rigid facade mineral wool slabs and combined systems of polystyrene and basalt fiber insulation;
   phenolic and urea-formaldehyde foams for well masonry walls;
   block thermal insulation made of cellular concrete and expanded clay, polystyrene foam concrete for laying single-layer self-supporting walls.

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