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Thermal conductivity of granular insulation in conditions of soil freezing

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Abstract. Thermal insulation materials are widely used in engineering practice to reduce the depth of seasonal freezing. The effective thermal conductivity of the material is the main criterion for predicting the freezing depth of the structure base and determining the required thickness of the thermal insulation layer. However, the effective thermal conductivity of granular thermal insulation materials can significantly depend on the seasonal temperature, hydrological conditions of the soil and the degree of water content of the material. In this regard, calculating the effective thermal conductivity of granular thermal insulation materials in natural conditions is an urgent scientific and practical task. Granular foam-glass ceramic with a bulk density of 250 kg/m3 was used in the study. To solve the problem, we employed an experimental set to simulate the natural conditions of heat transfer in a horizontal layer, which makes it possible to change the magnitude and direction of the temperature gradient. It was established that the magnitude and direction of the temperature gradient have no significant influence on the layer of granules with a size of 5–10 mm. A predictive calculation of the temperature fields of the roadbed using experimental values depending on the water content degree was carried out. It was found that the depth of freezing of the roadbed covered with a 20 cm layer of foam-glass ceramic with effective thermal conductivity of 0.075, 0.111 and 0.138 W/(m·°C), respectively, is 12, 3.8 and 3 times lower than without the thermal insulation layer. A graphical interpretation of the temperature field in the form of -2°C isotherms shows that there is a dangerous zone of intense frost heaving with a depth of 58 cm forming at the roadbed without thermal insulation. Complete absence of zones of intense frost heaving in the roadbed covered with granular foam-glass ceramic was confirmed.

1. *Introduction*

Ensuring the reliable and stable functioning of engineering structures in conditions of seasonal freezing and thawing of their bases is an urgent engineering task. Linear objects such as highways and railways, pipelines, etc., as well as buildings with shallow foundations are at risk of deformation. For example, a quarter of the entire budget of the Swedish Road Administration is spent on the annual elimination of the consequences of frost heaving of the roadbed [1]. Frost heave deformations are due to the presence of three factors at the base of the structure: frost susceptible soil, high soil water content and negative temperature. Depending on the listed factors, there are three ways to limit frost heaving process:

1. Replacement of frost susceptible soil with the one less sensitive to heaving.
2. Reducing soil water content due to drainage measures.
3. Covering the base with a layer of thermal insulation material.

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Special methods of engineering practice to protect structures from frost heaving deformations are constantly being improved [2–6]. According to a number of experts, one of the most effective and cheap ways to reduce the depth of seasonal freezing of bases is the use of thermal insulation materials [6–8]. These materials must have low thermal conductivity, sufficient compressive strength and low water absorption capacity.

Such lightweight aggregates as expanded clay and crushed foam glass as well extruded polystyrene boards are used in modern engineering practice [7–11]. The main advantage of extruded polystyrene boards is the lowest thermal conductivity during the entire period of operation, since the material does not absorb moisture. At the same time, the volumetric water absorption of lightweight aggregates can reach 30 % [10, 11]. Convection, grain size, layer compaction degree, etc. can have a significant effect on heat transfer in the layer of lightweight aggregates. In this regard, the thickness of the layers of lightweight aggregates can be several times greater than that of extruded polystyrene foam.

As an example, we can consider the temperature monitoring data of an experimental road section in Norway, where extruded polystyrene boards and lightweight aggregates were used [8].It was found that the extruded polystyrene boards and crushed foam glass layers 3 and 15 cm thick, respectively, have equal thermal resistance. Thus, the required thickness of crushed foam glass insulation layer is 5 times that of polystyrene boards. In the case of using expanded clay, a layer 7 times the thickness of polystyrene boards layer is required.

Despite this, a number of studies indicate the successful use of lightweight aggregates in road construction in Norway, Sweden and Finland. [1, 7, 10, 11]. The standards governing the use of lightweight aggregates on heaving road sections have been developed in these countries. The granular structure of lightweight aggregates is considered an important advantage in the art. Unlike extruded polystyrene boards, mechanized laying is possible in this case. In addition to performing thermal insulation functions, the layer of lightweight aggregates is drainage. Due to climatic and geological conditions, structural layers above extruded polystyrene boards can accumulate water. Under the same conditions, water drainage through the insulation lightweight aggregates can have a positive effect on the stability of the engineering structure.

The foregoing testifies to the relevance and practical significance of the use of lightweight aggregates during construction under conditions of seasonal soil freezing. Foam-glass ceramics is an alternative thermal insulation lightweight aggregate, which has recently found application in industrial and civil construction [12–14]. Granular foam-glass ceramic have a closed porous structure, due to which the volumetric water absorption of the material is about 6% [15–18].

A significant advantage of granular foam-glass ceramic is a widespread raw material base: opal-cristobalite (diatomite, tripoli, flask) and zeolite-bearing rocks. Their deposits are widespread throughout Russia, which makes it possible to organize the production of material near the construction site [14, 15]. Due to the high length of the country, a reduction in the distance of transportation of thermal insulation material can reach several thousand kilometers, which will give a significant economic effect. Such lightweight aggregates as crushed foam glass and expanded clay are produced, respectively, from waste glass and special types of clays that significantly limits their raw material base.

At present, experience has been accumulated in the experimental use of granular foam-glass ceramic. Temperature monitoring of the experimental section of the existing highway in the south of the Tyumen region (Russia) has been carried out since 2016. In the same year, on the section of the Trans-Baikal Railway (Russia), the material was used to insulate drainage reinforced concrete structures in order to exclude freezing of drainage waters in winter [20]. Based on the positive experience of the experimental use of the material, since 2017 its practical application in construction is regulated by the Russian State rules and regulations: SP 313.1325800.2017 “Automobile roads in permafrost regions. Design and construction rules”.

One of the tasks for the further development of the use of granular foam-glass ceramic in engineering practice is an accurate assessment of the effective thermal conductivity as a fundamental characteristic of thermal insulation material. A significant contribution to the value of the effective thermal conductivity of a granular material is made by the convective component of heat transfer. Its value depends on the magnitude and direction of the temperature gradient, the intergranular void volume, the shape of the grains, their size, etc. In nature, the process of heat transfer through granular material is accompanied by changes in soil and geological conditions, moisture gradient and temperature, which will eventually cause fluctuations in the effective thermal conductivity of the layer [21, 22]. For example, an increase in the volumetric water content in expanded clay to 20 % leads to an increase in its effective thermal conductivity from 0.11 to 0.21 W/(m·°C) [9, 10]. The above research data [8] refer to only one season of freezing-thawing of the roadbed (from November to March). Therefore, it is impossible to reliably assess the influence of water saturation and other factors on the change in the effective thermal conductivity of granular heat insulation layers over a longer period.

Unfortunately, the above-mentioned features of heat and mass transfer and possible seasonal fluctuations in the values of the effective thermal conductivity are not taken into account in modern numerical methods for calculating the temperature fields of the bases [23, 24]. As a rule, one averaged value is taken in the calculations, which is incorrect and leads to a discrepancy between the actual and calculated values of the base temperature. In this regard, the aim of the work was to study the influence of environmental factors corresponding to seasonal freezing on the effective thermal conductivity of granular foam-glass ceramic layer. The solution to this problem is of great practical importance in the design and assessment of the bearing capacity of the bases of engineering structures in areas of seasonal soil freezing. Correction of the effective thermal conductivity values when calculating the temperature fields will make it possible to more accurately predict the occurrence of dangerous zones of frost heaving in the base and determine the required thickness of the thermal insulation layer.

A review of literary sources has shown that the problem posed is highlighted in most detail in the works [21, 25]. A significant effect of the grain size, direction and magnitude of the temperature gradient on the effective thermal conductivity and free convection in the layer of granular materials had been established by the authors. Tested materials intended for road construction were placed in experimental setups, which were an insulated box with internal dimensions of 1 m × 1 m × 1 m. Nevertheless, the experimental technique had the following disadvantages:

1. Heat flow sensors were installed only at the top of the test layer, as a result the heat balance and heat flow dissipation by the side walls of the setups cannot be evaluated.

2. The dimensions of the setups were not related to the average grain size of the materials under study, which varied from about 10 to 100 mm. For example, according to the requirements of Russian State Standard GOST 7076-99, the thickness of the layer of granular material during the study of its effective thermal conductivity must be at least 10 times the average grain size, while the length of the inner horizontal edge of the box must be at least 5 times the thickness of this layer. Therefore, the minimum internal length and width of the box must be 5 m.

3. The average experimental error of the measuring system was 0.11 W/(m·K), while the effective thermal conductivity of the studied materials themselves: expanded clay and crushed foam glass was 0.1 and 0.115 W/(m·K), respectively.

In this regard, one of the tasks for solving the problem posed was the development of an experimental technique for determining the effective thermal conductivity of granular foam-glass ceramic, taking into account the mentioned above features of its application.

2. Methods

The study was carried out using foam-glass ceramic with a fraction of 5–10 mm. The properties of the material were determined in accordance with the method of Russian State Standard GOST 9758-2012 and had the following values: bulk density 250 kg/m^3, compressive strength in the cylinder 1.8 MPa, moisture 0.2 %, water absorption by volume 7 %. The choice of the fraction was justified by the fact that foam-glass ceramic with a grain size of less than 5 mm has a higher thermal conductivity and water absorption. In this regard, the use of fine fractions in the bases is unjustified.

The solution to the problem of determining the effective thermal conductivity was carried out using an experimental setup for simulating the natural conditions of heat transfer in a horizontal layer of granules. The design of the experimental setup and the calculation of the effective thermal conductivity were carried out in accordance with the requirements of Russian State Standard GOST 7076-99. A cross-sectional view of setup is shown in Figure 1. The body of the setup is made in the form of a horizontally located disk. The bottom, cover and side walls 5 are made of extruded polystyrene boards having a thermal conductivity of 0.033 W/(m·°C). The width of the walls is 12.5 cm, the thickness and diameter of the bottom and cover are 10 and 125 cm, respectively.

A layer of granulated foam-glass ceramic 2 with a thickness of 10 cm is placed in the setup body. The thickness of the layer was taken taking into account the tenfold excess of the largest grain foam-glass ceramic, equal to 10 mm. The diameter of layer 2 (100 cm) was taken taking into account the tenfold excess of its thickness. The layer 2 was leveled and tamped by hand to a compaction factor of 1.2. As a result, the density of the material in the compacted layer was 300 kg/m^3.

There are identical thermostating systems made of copper tubes 4 with a diameter of 12 mm on the upper and lower sides of the foam-glass ceramic layer 2. The upper and lower thermostating systems 4 are connected to separate thermostat, each of which set the temperature up and down respectively. Two counter-flow loops on each side of layer 2 are formed by the movement of the coolant in tubes 4. The direction of the coolant flow is shown by arrows at the top in Figure 1.

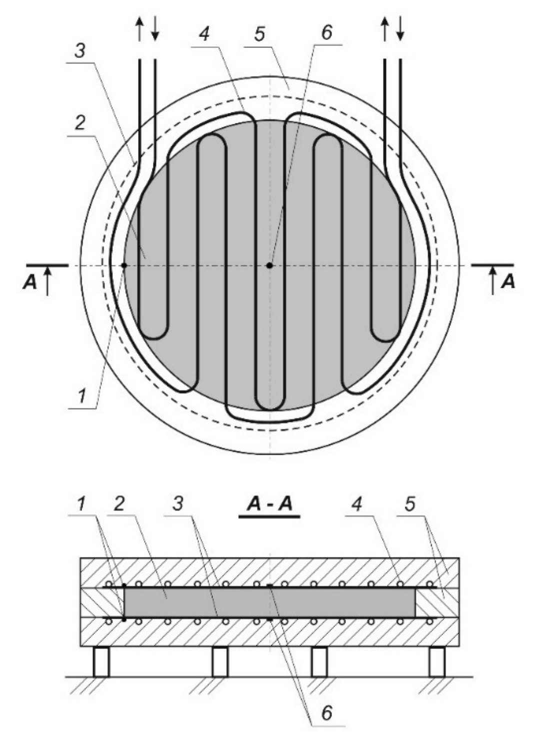

Figure 1. Experimental setup (cross section): 1 – Side temperature sensors; 2 – Foam-glass ceramic layer; 3 – Steel sheets; 4 – Tubes of the thermostating system; 5 – Expanded polystyrene; 6 – Heat flow sensors combined with temperature sensors.

The tubes of system 4 are attached to steel sheets 3 with a thickness of 3 mm. Due to the counter-flow loops of thermostating systems the temperature is uniformly distributed over the surface of the sheets 3 that are in contact with the upper and lower surfaces of layer 2. The sheets 3 serve to equalize the heat flow and more uniform temperature transfer from the coolant to the granular material. The diameter of the sheets 3 is 10 cm larger than the diameter of layer 2 in order to minimize the lateral temperature gradient in layer 2. The counter-flow loops of the upper and lower thermostating systems 4 have an increased diameter for the same purpose.

Due to the above-described setup design (Figure 1) the required temperature can be set and maintained on the upper and lower steel sheets 3. As a result, a vertical temperature gradient and its direction in the investigated layer 2 are set. For example, there is an upward temperature gradient at freezing conditions because the base temperature is higher than the air temperature. During defrosting, when the air temperature rises above the base temperature, the gradient is reversed.

From the above ratios of the thickness and diameter of layer 2, it follows that the dimensions of the setup directly depend on the size of the largest grain. For example, an increase in the maximum grain size from 10 to 20 mm will cause an increase in the area of steel sheets 3 by 4 times. As a result, it will be necessary to increase the sheets thickness, use a more complex thermostating system 4, increase the power or the number of thermostats, etc. The listed design features served as a rationale for the choice of the 5–10 mm fraction in these studies. This fraction can be used in bases along with a larger one (for example, 10–20 mm), however, the determination of the effective thermal conductivity of larger fractions will require separate studies using more complicated setup.

The value of the temperature gradient is measured using temperature sensors 6 with an absolute error of ± 0.1 °C. Temperature sensors 6 are combined with heat flow sensors in order to place them on the central setup axis. Due to the fact that the material of layer 2 is represented by individual grains, the sensors 1 and 6 are fixed on steel sheets 3 using a heat-conducting paste. Temperature sensors 1 are designed to assess the horizontal (lateral) temperature gradient caused by the influence of the ambient temperature. The air temperature in the room where the setup was located was maintained at 20 ± 0.2 °C.

The heat flow density in layer 2 is determined using heat flow sensors 6 with an error of ± 0.1 W/m^2. Sensors 1 and 6 are connected to an analog-to-digital converter that records temperature and heat flow data at 20 minute intervals. The measuring cycle begins from the moment the upper and lower thermostating systems are switched on until a steady state heat flow in layer 2 is formed. The heat flow in layer 2 was considered as steady state under the following conditions:

1. Deviations of the values of five consecutive measurements of temperature and heat flow density should not exceed the absolute error of sensors 1 and 6 (Figure 1).

2. The difference between the readings of the side and central temperature sensors (1 and 6, respectively) should not exceed the absolute error of this sensor.

3. The values of the heat flow density measured by the upper and lower sensors should not differ by a value exceeding their absolute error.

If at least one of the above conditions was not met, then the number of measurement intervals increased until it was fulfilled, or measurements were repeated from the beginning of the measuring cycle. If the above conditions are met, the effective thermal conductivity of layer 2 was calculated by the formula:

$$\lambda = q\frac{h}{t}$$

where λ is effective thermal conductivity, W/(m·°C); q is heat flow density, W/m^2; h is test material layer thickness, m; t is absolute value of the temperature difference between steel sheets 3, determined by sensors 6, °C.

The q value was obtained by averaging the readings of the upper and lower sensors 6 (Figure 1). The arithmetic mean λ of three measurement cycles was taken as the final result. The absolute error of the λ value was calculated by the formula [26]:

$$\Delta\lambda = \lambda\sqrt{\left[\frac{\Delta q}{q}\right]^2 + \left[\frac{\Delta h}{h}\right]^2 + \left[\frac{\Delta t}{t}\right]^2}$$

where $\Delta\lambda$, Δq, Δh and Δt are the absolute errors of the values of λ, q, h (±0.5·10^{-3} m) and t, respectively.

3. Results and Discussion

3.1. Laboratory thermal conductivity test

The obtained values of t, q and the results of calculating λ of tested layer are presented in Table 1. For measurements 1–3 and 4–6 heat flow was directed upward and downward respectively. Under natural conditions, these temperature gradients correspond to freezing and thawing of bases, i.e. negative (and close to 0 °C) temperature can be both above and below the thermal insulation layer. Numbers 1–6 corresponded to measurements of tested layer in a dry state.

Table 1. Measurement results.

No	Compacted layer properties		Temperature, °C			q, W/m^2	λ, W/(m·°C)	$\Delta\lambda$·10^{-3}, W/(m·°C)
	Density, kg/m^3	Volumetric water adsorption, %	top	bottom	t			
1	300	0	0.8	10.5	9.7	7.3	0.076	1.4
2	300	0	2.9	19.4	16.5	12.5	0.076	0.9
3	300	0	-3.2	22.3	25.5	19.6	0.077	0.6
4	300	0	11.0	0.9	10.1	7.4	0.073	1.3
5	300	0	20.1	3.1	17.0	12.7	0.075	0.8
6	300	0	19.9	-3.2	23.1	17.2	0.074	0.7
7*	340	0	1.6	19.1	17.5	15.5	0.089	0.9
8	324	3.7	1.7	16.6	14.9	16.5	0.111	1.1
9	346	7.0	1.4	15.6	14.2	19.7	0.138	1.4

*Grains size of 2.5–5 mm

It follows from Table 1 that a change in the value of t for measurement numbers 1–3 and 4–6 does not significantly affect the values of λ. Average values of λ with upward heat flow (numbers 1–3) and reverse (numbers 4–6) differ by 1·10^{-3} W/(m·°C). In view of the fact that the average value of $\Delta\lambda$ for measurements 1–6 is ±1·10^{-3} W/(m·°C), it can be concluded that the influence of the heat flow direction and the values of t on λ is insignificant. Thus, according to the averaging of measurements 1–6, the value of λ for the 5–10 mm fraction in the dry state is 0.075 W/(m·°C).

Measurement umber 7 in the Table 1 shows the results of determining λ of a finer fraction of foam-glass ceramic with a size of 2.5–5 mm and a bulk density of 340 kg/m^3. As follows from the Table 1, the λ value of this fraction is almost 20 % higher in comparison with the 5–10 mm fraction. In this regard, the use of fractions with a grain size of less than 5 mm is less effective.

Due to the inevitable moistening and water absorption of granular foam-glass ceramic layer at the base, λ measurements in the water-saturated state were carried out. The results for the fraction 5–10 mm numbered 8 and 9 in Table 1. The water absorption of the granules by volume was 3.7 and 7 % in the first and second cases, respectively, which corresponded to the intermediate and maximum water absorption of the material.

The Table 1 shows that the λ values of measurements 8 and 9 exceed the obtained average λ of measurements 1–6 by approximately 1.5 and 1.8 times, respectively. Consequently, the effect of water saturation of granular foam-glass ceramic on the λ value is much more significant in comparison with the direction of the heat flow, t value and the size of the granules. In this regard, the use of the material in practice will require special methods to maintain the calculated thermal resistance of the layer, for example, the use of protective membranes, films, etc. In the case of direct contact of the layer granules with the soil, the λ value will fluctuate in the range from 0.075 to 0.138 W/(m·°C), depending on the degree of soil moisture at the base of the structure. As a result, in order to maintain the calculated thermal resistance of the layer, it will be necessary to increase its thickness up to 1.8 times.

For predictive calculations of the temperature fields of the bases and the freezing depth, two experimental values of λ can be distinguished for a layer of 5–10 mm fraction. In the event that the base is located in a high area with a low level of groundwater, an intermediate value of λ should be taken in the calculations, equal to 0.111 W/(m·°C). If the base is located in an area characterized by the accumulation and stagnation of surface water, which will contribute to the maximum water saturation of the thermal insulation material, then the maximum λ value of 0.138 W/(m·°C) should be taken.

The result obtained can be compared with the data of other authors. For example, in studies [21], the value of λ in the dry state was experimentally established for crushed foam glass aggregate with a close bulk density equal to 223 kg/m^3. However, the average grain size of the fraction 10–60 mm was 4.7 times greater than that of the foam-glass ceramic. Taking into account the downward heat flow condition the experimental value of λ was 0.34 W/(m·K), which is 4.5 times more than for foam-glass ceramics in a dry state. Apparently, such a significant difference is caused by the influence of free convection due to the larger grains of crushed foam glass.

3.2. Mathematical modeling

For the purpose of a comparative assessment of the influence of three experimental λ values on the base freezing depth, a calculation was carried out using finite-difference methods of mathematical modeling [23, 24]. The calculations were carried out on the example of a highway located in the south of the Tyumen region, Russia (Golyshmanovsky district). The area is distinguished by a large seasonal freezing depth. The average January temperature between 2006 and 2019 is -17.9 °C.

The right side of the typical road cross section is shown at the top in Figure 2 (the left part is symmetrical to the road axis and is not shown). The thickness of insulation layer 1 was set taking into account the provision of a deviation of ±1 cm during mechanized compaction of material with specialized road equipment. The main calculated characteristics of the layers are presented in Table. 2. For the pavement layer, the average value of thermal conductivity of asphalt concrete and crushed stone is taken. The heat of the phase transition of pavement materials was not taken into account in the calculations.

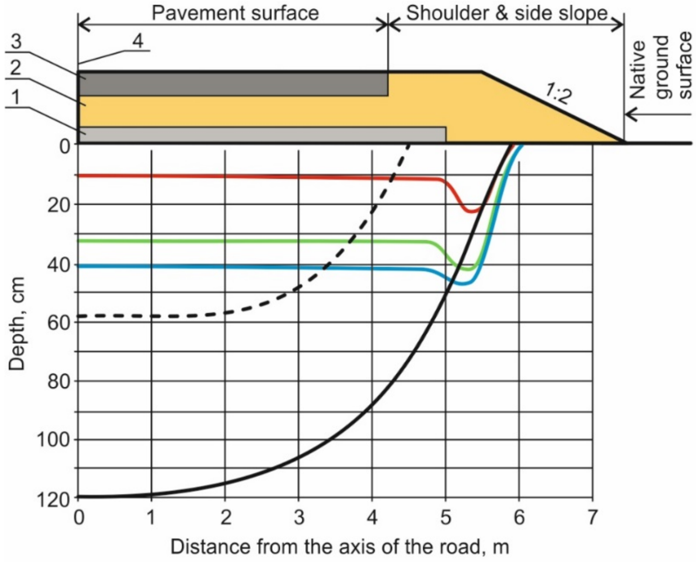

Figure 2. Road cross section and calculation results: 1 – Foam-glass ceramic layer (20 cm); 2 – Coarse sand layer (38 cm); 3 – Pavement: asphalt concrete and crushed stone (42 cm); 4 – Road axis. Red, green and blue lines correspond to -0.5 °C isotherms with λ 0.075, 0.111 and 0.137 W/(m·°C), respectively. Black solid and dotted lines correspond to -0.5 and -2 °C isotherms without insulating layer. The scale of the vertical axis is increased by 4 times for clarity.

Because the thickness of the insulation layer is significantly less than the base freezing depth, its λ values in the thawed and frozen state were equated to the corresponding experimental λ values obtained above. The phase transition heat of the foam-glass ceramic in the water-saturated state was not taken into account in the calculations for the same reason. The specific heat capacity of the material was taken equal to the reference value for silicate glass, which is 840 J/(kg·°C) [27], due to the close chemical composition [14, 15]. Therefore, taking into account the density of the heat insulation layer in dry compacted state (300 kg/m^3), its calculation specific heat capacity per 1 m^3 is 252 kJ/(m^3·°C).

Table 2. Characteristics of layers and base.

No	Name of the material	Thermal conductivity, W/(m·°C)		Heat capacity, kJ/(m^3·°C)		Phase transition heat, MJ/m^3
		thawed	frozen	thawed	frozen	
1	Pavement	2.05		1870		-
2	Coarse sand	1.97	2.15	2250	1790	82
3	Silt sandy loam	2.02	2.30	2740	2120	96

The roadbed (subsoil) was represented by silty sandy loam with high frost heave rate of 9 % and a low degree of salinity. This type of soil is widespread in the region under consideration. In accordance with the Russian State rules and regulations SP 25.13330.2012 "Bases and foundations on permafrost soils", the calculated temperature of the subsoil phase transition was -0.5 °C.

When solving an axisymmetric problem, the computational domain was represented by a square with sides of 15 m. The axis of the road (Figure 2) coincided with the left side of the computational domain. The horizontal dimension of the computational domain was set taking into account the two-fold excess of the foot of the road structure (7.5 m, Figure 2), and vertically, taking into account the attenuation of annual air temperature fluctuations at a depth of 15 m [28]. Boundary conditions of the first kind with a constant temperature of 0.9 °C were set on the lower side. According to Russian State rules and regulations SNIP 23-01-99 this temperature corresponds to the average annual air temperature in the area under consideration. Boundary conditions of the second kind (without heat flow) were set on the lateral sides of the computational domain.

In the three types of surfaces of the computational domain (Figure 2) boundary conditions of the third kind were set. Average monthly values of air temperature, wind speed, and thickness of snow cover on the surface were calculated for the period from 2006 to 2019 according to the data of meteorological station No. 28478 (Tyumen region, Golyshmanovsky district). Due to snow removal in winter the snow cover on the pavement surface was not taken into account in the calculations. For this reason, a doubled layer of snow was taken on the road shoulder and the side slope. In order to reduce the freezing depth of these areas under the influence of the exposed layer 3, the thermal insulation layer 1 had an increased width

(Figure 2). A sod cover with a thickness of 10 cm and a thermal conductivity of 0.75 W/(m·°C) was taken into account in the road shoulder, the side slope and the native ground surface.

The initial calculation conditions corresponded to the date of October 1, 2020 and a surface temperature of 6 °C. The final calculated date March 15, 2023 corresponded to the maximum seasonal freezing depth of the base. The calculation results in the form of lines denoting the isotherms are shown in Figure 2. Isotherms of -0.5 °C, corresponding to the phase transition temperature of sandy loam, characterize the base freezing depth.

As follows from the calculation results in Figure 2, the freezing depth of the base without taking into account the insulation layer is characterized by black solid -0.5 °C isotherm. The maximum value of the freezing depth of 120 cm near the axis of the road was reached. Calculations taking into account the thermal insulation layer with λ equal to: 0.075, 0.111 and 0.137 W/(m·°C) are characterized by red, green and blue -0.5 °C isotherms, respectively. Neglecting the bends of the isotherms at a distance of 5–6 m from the axis of the road, it was found that the computational freezing depth in this case is 10, 32 and 40 cm at λ equal to: 0.075, 0.111 and 0.137 W/(m·°C), respectively.

It is known that the degree of frost heaving significantly depends on the type of soil and its moisture content. The frost heave process begins to develop most intensively at a certain temperature, for example, for loams from -1.5 to -2.5 °C [28]. Assuming this temperature for sandy loam equal to -2 °C, then the zone of frost heaving at the base will be limited by the -2 °C isotherm. A graphical interpretation of the calculated temperature fields without an insulating layer shows the -2 °C isotherm in Figure 2, marked with a black dotted line. This isotherm limits the dangerous zone of intense frost heaving to a depth of 58 cm near the axis of the road. Taking into account the accepted high frost heave rate of the base soil, the absolute deformation of frost heaving near the axis of the road can reach 5 cm. As a result, the annual freezing-thawing processes will cause seasonal deformations of the pavement surface and its gradual destruction.

The formation of the -2 °C isotherm taking into account the variations in experimental λ values of the thermal insulation layer was not confirmed in Figure 2. At the same time, there are no deformations of frost heaving of the roadbed, causing the pavement surface destruction, which significantly increases the overhaul interval of the road.

The results of mathematical modeling can be compared with the experimental data of field test of crushed foam glass with a bulk density of 220 kg/m^3 in climatic conditions of Norway [8]. A layer of the material 15 cm thick ensured that a positive temperature at the roadbed had been maintained. On a road section without thermal insulation, the 0 °C isotherm at a depth of 35 cm had been reached.

The advantage of using granular foam-glass ceramic is not only in reducing the freezing depth of the base. It is known that during the construction of highways in areas with unfavorable soil and hydrological conditions, there is a need for a frost-protective layer. The thickness of this layer, ensuring the exclusion of freezing of the base, can be more than two meters (depending on the climatic zone) [29]. For the construction of frost-protective layers of highways, as a rule, coarse sands are used. Taking into account the high length of the road under construction, the transportation distance of coarse sands can exceed 500 km. Thus, the use of granular glass-ceramic foam can give a significant economic effect as a result of reducing the volume of materials transportation and earthworks.

4. Conclusion

1. The experimental values of the effective thermal conductivity of granular foam-glass ceramic with a fraction of 5–10 mm in a dry and water volumetric saturated states of 3.7 and 7 % were established: 0.075, 0.111 and 0.138 W/(m·°C), respectively. The effect of changing the direction and magnitude of the temperature gradient was insignificant, since it is within the absolute error of the measuring setup.

2. A predictive calculation of the temperature fields of the roadbed using experimental values depending on the water content degree was carried out. It was found that the freezing depth of the roadbed covered with a 20 cm layer of foam-glass ceramic with effective thermal conductivity of 0.075, 0.111 and 0.138 W/(m·°C), respectively, is 12, 3.8 and 3 times lower than without the thermal insulation layer. Due to graphical interpretation of the temperature field in the form of -2 °C isotherms at the roadbed without thermal insulation the formation of a dangerous zone of intense frost heaving with a depth of 58 cm was shown. The complete absence of zones of intense frost heaving in the roadbed covered with granular foam-glass ceramic was confirmed.

3. The obtained experimental data can be applied in methods for calculating temperature fields in order to assess the risk of occurrence of cryogenic zones in bases using granular foam-glass ceramic.

4. Due to the wide mineral resource base, the production of granulated foam-glass ceramic can be deployed in territories remote from industrialized regions, for example, in the Far North and the Arctic. The

development of these territories will require both the modernization of the existing and the creation of a new transport infrastructure, which requires the use of special technologies and innovative road materials of local production.

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