Magazine of Civil Engineering

ISSN 2712-8172

journal homepage: http://engstroy.spbstu.ru/

DOI: 10.34910/MCE.110.3

Thermal insulation systems for road bases with foam glass gravel

***V.S. Semenov*[a]*, *I.V. Bessonov*[b], *Zh.A. Zhukov*[a], *E.A. Mednikova*[a], *I.S. Govryakov*[b]**

[a] *National Research Moscow State Civil Engineering University, Moscow, Russia*

[b] *Research Institute of Building Physics (NIISF RAACS), Moscow, Russia*

**E-mail: science-isa@yandex.ru*

Keywords: foam glass gravel; heat-insulating material; permafrost; road system; exploitation stability; soil; freezing level; temperature field

Abstract. The article discusses the systems of roadbed construction on permafrost and heaving soils with foam glass gravel backfill. The aim of the research was to substantiate the expediency of using foam glass gravel in roadway insulation systems on problematic, including heaving and permafrost soils. This goal was achieved by determining the properties of foam glass gravel, as well as calculating the thermal characteristics and temperature fields in the roadbed. The strength of foam glass gravel, depending on its degree of compaction (from 10 to 50 %), is in the range of 0.90...1.58 MPa, and the thermal conductivity coefficient is from 0.087 to 0.099 W/(m°C). It was found that the water absorption of gravel by volume does not exceed 1.8 %, and the sorption humidity does not exceed 4.2 %. The novelty of the work lies in a comprehensive study of insulation systems using domestically produced foam glass gravel using digital imitation of heat transfer and modeling of the formation of temperature fields. It has been established that the use of heat-insulating backfill of foam glass gravel with a thickness of 0.25 m allows to protect the permafrost soil of the road base from thawing, and to limit the freezing depth to 0.2 m, versus 2.6 m without heat-insulating layer – in case of protection of the road base from freezing. The significance of the research is the development of constructive solutions for the use of foam glass gravel in roadway insulation systems, arranged on problem soils in permafrost conditions and on soils with frost heaving.

1. Introduction

The service life of the road pavements is determined by a combination of several factors. Firstly, this is the type of road structure, including the construction of the base and the type of pavement (cover), and the design of the inner layers that take loads and transfer these loads to the ground. Secondly, this is the type of base soil, its condition and stability, including the presence of permafrost, wetlands, water hoses, etc. Thirdly, this is the quality of road work, that is, the fulfillment of all normative requirements to these works.

Insulating materials used in pavement systems should have low heat conductivity and water absorption, have high resistance to aggressive environments and biological corrosion, high frost resistance, good strength properties [1–3]. These requirements are best met by plate products based on extruded foamed polystyrene and foam glass, as well as foam glass gravel, manufactured on specialized lines.

In the harsh permafrost conditions, the construction of thermal insulation layers (from extruded foamed polystyrene: XPS-plates) allows the permafrost soils to be kept in their natural state, which prevents

Semenov, V.S., Bessonov, I.V., Zhukov, Zh.A., Mednikova, E.A., Govryakov, I.S. Thermal insulation systems for road bases with foam glass gravel. Magazine of Civil Engineering. 2022. 110(2). Article No. 11003. DOI: 10.34910/MCE.110.3

thawing and excludes subsidence of the subgrade. Also noteworthy is the use of XPS -plates (blocks) in the construction of lightweight embankments on weak foundations.

When using the technology of building light embankments from extruded foamed polystyrene blocks, problems associated with insufficient bearing capacity of the soil, the possibility of large settlements and a long period of foundation stabilization are solved. The term and cost of construction is reduced [4–6].

The disadvantage of such systems is the fact of using plate (piece) products, i.e. the presence of seams and contact areas between the plates. During operation, due to seasonal deformations or changes in the level of groundwater (on soft soils), the base moves and its configuration changes. This can lead to a gradual opening (increase) of the gaps between the plate products, which leads to the creation of areas of intense heat and mass transfer, and therefore to the violation of the thermal integrity of the insulating shell.

Laying boards made of extruded foamed polystyrene requires careful preparation of the base and is highly labor intensive. In addition, during operation, the plates are deformed, crumbled and, over time, lose their heat-insulating properties.

The use of backfill insulation makes it possible to form a uniform insulating shell. Foam glass gravel is a filling thermal insulation. Such material is used as a backfill to thermal insulation the foundations of low-rise buildings, the brick walls of the well masonry or Gerard masonry, as well as to strengthen weak soils and the sub ballast layer of the pavements. Foam glass gravel produced on special lines has a bulk density of 120…200 kg/m^3 and grain size of 40...60 mm.

For the foam glass production recycled glass obtained from bottle fight, defective automotive glass and double-glazed window battle are used as a raw material. An analysis of the glasses recommended by our and foreign researchers to obtain high-quality foam glass showed that the glasses synthesized in the systems SiO_2–Al_2O_3–MgO–CaO–R_2O and SiO_2–B_2O_3–MgO–CaO–R_2O found wide application in the production of foam glass. We can conclude that aluminosilicate and aluminoborosilicate glasses most fully satisfy the requirements for the foam glass quality. In Russia, to obtain heat-insulating foam glass, glass masses are most often used that are close in chemical composition to aluminum-magnesium glass [7–9].

An analysis of the foam glass gravel use shows that about 30 % falls on roofs and about 40 % on stylobates. The remaining volume is used in landscape design, road construction, in the overhaul of blocks of flats and foundations. The forecast shows that, due to its properties, for the period 2020–2022 under favorable conditions, foam glass gravel will occupy more than 2 % of the total market of thermal insulating materials and will amount to at least 1 million m^3. Abroad, foam glass gravel has been used in road systems since the mid-80s of the last century. These technologies are most common in the Scandinavian countries: Finland, Sweden, Norway. At the same time, the duration of the winter period, as well as the presence of heaving soils in the regions of the Russian Federation east of the Urals, impose special requirements on road structures.

As a result of the analysis and experimental studies, it was established that the materials used in road insulation systems should have low thermal conductivity and water absorption, have high resistance to aggressive ambience and biological corrosion, have high frost resistance and high strength characteristics.

The purpose of the research was to substantiate the expediency of using foam glass gravel in roadway insulation systems on problematic, including heaving and permafrost soils, based on studying the patterns of formation of temperature fields in insulation systems.

To achieve the goal of the study, it was envisaged to perform the following particular tasks:

- study of the properties of foam glass gravel at various degrees of its compaction;
- development of soil insulation systems in conditions of its preservation in a frozen state (protection against thawing) and in conditions of maintaining positive temperatures in it (protection against frost heaving);
- calculation of thermal characteristics and temperature fields in roadway insulation systems using the THERM computer program.

2. Materials and Methods

The tests of the properties of crushed glass foam were carried out in accordance with the current standard methods. The calculation of thermal characteristics and temperature fields in roadway insulation systems was evaluated using a special computer program THERM, developed by Lawrence Berkeley Laboratory (LBNL), University of California, USA.

In the experiments, foam glass gravel with a bulk density of 180 kg/m^3 was used (Fig. 1).

Figure 1. Foam glass gravel.

The maximum degree of compaction of foam glass gravel was determined on the installation, equipped with a vibrator and weights with a total weight of 250 kg (Fig. 2). The cylindrical metal-plastic container had a diameter of 500 mm and a height of 380 mm. The dimensions of the container are selected in such a way that they allow placing at least 6 pieces of gravel in height and width. Foam glass gravel was poured into the container, shaking was performed for natural compaction. The amount of crushed stone was selected so that when lowering the loads, the lower edge of the lower disc was flush with the upper level of the container. It was found that the maximum degree of compaction of foam glass gravel with a bulk density of 180 kg/m^3 and a fraction of 30…60 mm is 50 %.

Figure 2. Carrying out experimental determinations of the maximum degree of compaction of foam glass gravel.

The compressive strength in the cylinder was determined on foam glass gravel, filled in a container and compacted with a given coefficient. A container (a metal cylinder with an inner diameter of 308 mm and a height of 210 mm) with a sealed foam glass gravel was installed on the lower platform of the press (Fig. 3). The compressive strength of foam glass gravel was taken as the arithmetic mean value of five tests [10–12].

Figure 3. Experimental determination of the compressive strength of foam glass gravel at different degrees of compaction.

Determination of the thermal conductivity coefficient of foam glass gravel at various degrees of compaction was carried out in a climatic chamber consisting of two chamber (cold and warm) and an aperture in which the studied material was placed (Fig. 4). In the cold zone, a temperature of minus 10 °C was established; in the warm zone, a temperature of + 20 °C was maintained.

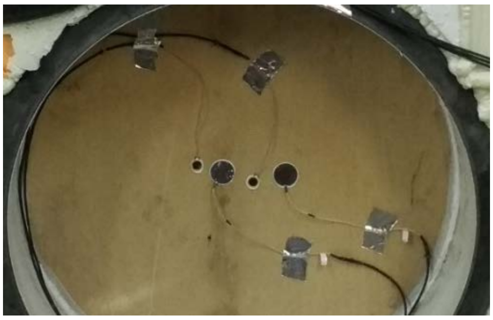

Figure 4. Experimental determination of thermal conductivity of foam glass gravel in a dry state at various degrees of compaction.

The tests were carried out in accordance with the GOST R 54853-2011 methodology with the following changes. Cylindrical containers were used as a test structure, in which foam glass gravel was compacted. The walls of the container on the warm and cold sides consisted of 10 mm thick plywood sheets tightly adjacent to the gravel, the thermal resistance of which was taken into account when calculating the thermal conductivity. The internal dimensions of the container in the plane of movement of the heat flow must exceed the average size of the crushed stone granule (in an unconsolidated state) by at least 5 times. Containers with foam glass gravel were installed in the opening of the climate chamber. Each container was insulated along the side faces, so that the thermal resistance along each of the product faces was at least 5 (m^2·°C)/W. Heat flux density measurements were carried out in accordance with GOST 25380-2014. Temperature sensors were installed on the outer (face of the sample facing the cold zone) and inner (face of the sample facing the warm zone) surfaces of each sample. Converters (sensors) of the heat flux were installed on the inner face. In the experiment performed, the horizontal direction of the temperature gradient was taken. At the same time, taking into account the isotropy of the properties of compacted foam glass gravel and its uniform distribution in the test container, it is permissible to accept the obtained value of the thermal conductivity coefficient in further calculations, with the vertical direction of the heat flow.

The thermal conductivity coefficient of foam glass gravel was determined in dry and wet conditions. A certain amount of foam glass gravel was dried to constant weight at a temperature of (100±5)°C, and then kept in the laboratory for at least 24 hours (conditioning). Further foam glass gravel was tamped layer by layer in the container to the required degree of compaction.

The working density (ρ_w) of foam glass gravel was determined taking into account the degree of compaction (10 %, 20 %, 30 %, 40 % and 50 %). The established value of bulk density (ρ_b) was multiplied, respectively, by compression factors 1.1; 1.2; 1.3; 1.4 or 1.5. For example:

$$\rho_w = 1.3 \times \rho_b, \ \text{kg/m}^3. \quad (1)$$

The mass of gravel, m_g, kg, required for testing, was determined by the formula:

$$m_g = \rho_w \times V, \quad (2)$$

where ρ_w is working density, kg/m^3; V is the volume of the tank for determining the compressive strength in the cylinder, m^3.

The amount of gravel determined by formula (2) was poured in layers into a container, periodically compacting and ramming. Compaction was carried out by manual or mechanical tamping. Gravel compaction was carried out before filling the tank at the level of the upper edges. The coefficient of thermal conductivity was measured at an average temperature of backfill from gravel of 10 °C. Upon reaching the stationary thermal regime, the values of temperatures and heat fluxes were recorded and the equivalent thermal conductivity of foam glass gravel in the dry state was calculated.

Experimental studies were carried out to determine the strength of foam glass gravel by compression in a cylinder with a compaction degree of 10 %, 20 %, 30 %, 40 %, and 50 %. The strength of foam glass gravel was determined on samples compacted to working density. The mass of gravel, m_g (kg), required for testing, was determined by the formula (2). A cylinder with compacted foam glass gravel was installed on the lower platform of the press. A plunger with a diameter of 300 mm was used to load the surface of the gravel poured into the cylinder from 2 to 25 % relative deformation, that is, before crushing gravel by 2...25 % of the initial height. The arithmetic mean of the results of five tests was taken as the compressive strength in the cylinder of foam glass gravel.

The compressive strength in the cylinder at $N\%$ relative deformation $\left(R_{N\%}\right)$ of the gravel, MPa, was determined by the formula:

$$R_{N\%} = \frac{P}{F}, \tag{3}$$

where P is the load during compression of the aggregate, corresponding to $N\%$ relative deformation, N; F is the cross-sectional area of the plunger, mm^2.

At the same time, the main strength characteristic of foam glass gravel was taken to be the compression strength in a cylinder at 10 % linear deformation, as is customary for thermal insulating materials.

The water absorption of foam glass gravel was determined after being fully immersed in water for 24 hours according to the method of Russian State Standard GOST 17177. The average value of water absorption by volume was 1.8 %. The sorption moisture content of foam glass gravel was investigated according to the method of Russian State Standard GOST 24816-2014.

To study the properties of the pavement and to assess the possibility of its use on problematic soils, it is advisable to study the temperature fields formation in the road base with the help of modern computer analysis systems. These methods and the like ones are widely used in the study of multilayer insulation systems, including bases in contact with the soil [13–15]. Temperature fields were calculated using the THERM computer program based on the finite element method [16–18].

3. Results and Discussion

As the results of the experimental studies, the strength characteristics of bulk thermal insulation and the values of the thermal conductivity at various compaction degrees were determined. Design solutions for the isolation of pavement systems on problematic soils are proposed, and these solutions are evaluated using temperature field modeling in the road massive.

The results of experimental determinations of the compressive strength of foam glass gravel and thermal conductivity at various compaction degrees (squeezing in the cylinder) are given in Table 1. It was found that the compressive strength in the cylinder at 10 % relative deformation increases linearly in the range of compaction degrees from 10 % to 40 %, and practically does not change with further compaction.

Table 1. The results of experimental studies to determine the compressive strength of foam glass gravel in a cylinder and thermal conductivity at various compaction degrees.

The compaction degree of foam glass gravel, %	The average value of the compressive strength in the cylinder at 10 % deformation, MPa	The thermal conductivity coefficient of the foam glass gravel in dry state, W/(m·°C)
50	1.58	0.099
40	1.56	0.086
30	1.26	0.072
20	1.10	0.086
10	0.90	0.087

A decrease of the thermal conductivity coefficient was noted at a compaction degree of 30 %, which is explained by the densest packing of granules in the filling, with a minimum amount of intergranular space. An increase of the thermal conductivity coefficient at a compaction degree of 10 % and 20 % is due to an increase of the convective component of heat transfer (air movement) in an increasing volume of intergranular space. With a compaction degree of 40 % and 50 %, partial destruction of the foam glass granules occurs and the intergranular space is filled with small solid particles, which leads to an increase in thermal conductivity.

Studies of sorption properties showed the difference between the set of mass during adsorption and the drying rate – desorption of the foam glass gravel. The graph (Fig. 5) shows the hysteresis of material sorption. The moisture content of foam glass gravel at 100 % relative humidity was conventionally taken as the moisture content of the material by weight after complete immersion in water for 24 hours, followed by exposure to air for 24 hours (temperature 23±2 °C and relative humidity 97 %). It should be note that the hysteretic pattern of sorption-desorption is also characteristic of other types of highly porous materials and it can be explained by the conditions for the formation of polymolecular layers on the surfaces of the mineral matrix in open semi-closed and closed pores of the substance [19–21].

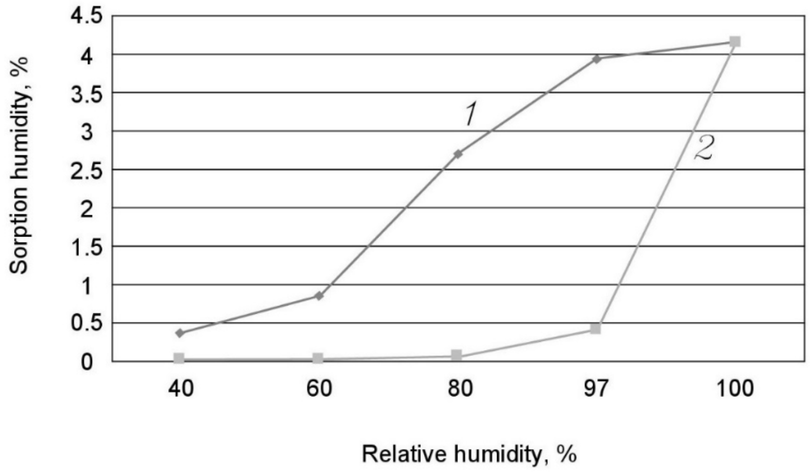

Figure 5. Hysteresis of sorption-desorption of foam glass gravel: 1 – sorption; 2 – desorption.

Based on the obtained values, the dependences of humidity and thermal conductivity, the coefficient of thermal conductivity increment for each percentage of humidity were determined, as well as the calculated values of thermal conductivity of foam glass gravel for operating conditions. The obtained results made it possible to justify the use of foam glass gravel into the insulating layers of the pavements arranged on problematic soils, including permafrost, heaving soils, etc.

The design of road insulation systems was carried out taking into account the principles of laying thermal insulation layers in pavement structures [22–24]. At the same time, two tasks were solved. The first task was to protect the permafrost soil of the base from potential thawing (preservation of permafrost and protection from thawing). The second task was to protect the soil from freezing (protection from soil swelling during freezing). Requirements for foam glass gravel are presented in Table 2.

Table 2. Normative values of the thermal conductivity coefficient of the foam glass gravel for operating conditions.

Indicator	Unit	Value
Coefficient of thermal conductivity in the backfill with compaction (1.3: 1) in a dry state	W/(m·°C)	0.072
Coefficient of thermal conductivity in the backfill with compaction (1.3: 1) in operating conditions	W/(m·°C)	0.085

Calculations of the temperature fields of the road surface using foam glass gravel were carried out using the THERM program developed by Lawrence Berkeley Laboratory (LBNL) of the University of California, USA (THERM Finite Element Simulator version 7.7.10.0, Copyright 1994-2019). This program is at the disposal of NIISF RAASN and is widely used in heat engineering calculations.

Protection against thawing was carried out by laying heat-insulating layers in the body of the embankment in the conditions of the spread of soil permafrost in the first road-climatic zone in order to preserve the soil in a solid-frozen state for the entire service life of the road and to prevent the embankment subsidence on thawing frozen soil.

The following boundary conditions are accepted in the calculations. Soil temperatures are taken from the gas industry worker's handbook table 4.13 [25]. The temperature of the permafrost soil in the climatic conditions of Yakutsk is the average temperature for 12 months at a depth of 0.8 m and is equal to minus 2.6 °C. The air temperature in the calculation is assumed to be 30 °C. The properties of soils and sand embankments were taken in accordance with Russian Construction Norms SP 25.13330.2016 Bases and foundations on permafrost soils (Table B.8).

The thermal conductivity coefficient of soil in a frozen state is taken in accordance with Table B.8. Characteristics of the materials of the layers of the road structure with foam glass gravel backfill: peat soil with a density of 400 kg/m^3; thermal conductivity coefficient in a frozen state of 1.45 W/(m°C); sand embankment with a density of 1400 kg/m^3, thermal conductivity coefficient of 2.48 W/(m°C), layer thickness of 400 mm; filling with foam glass gravel with a density of 140 kg/m^3, thermal conductivity coefficient of 0.085 W/(m°C), layer thickness of 250 mm (according to research data); asphalt concrete with a density of 2100 kg/m^3, thermal conductivity coefficient of 1.05 W/(m°C), two layers 50 mm thick [26–27].

Characteristics of the materials of the layers of the road structure without foam glass gravel backfill: peat soil with a density of 400 kg/m^3; thermal conductivity coefficient in a frozen state of 1.45 W/(m°C); sand embankment with a density of 1400 kg/m^3, thermal conductivity coefficient of 2.48 W/(m°C), layer thickness of 650 mm; asphalt concrete with a density of 2100 kg/m^3, thermal conductivity coefficient of 1.05 W/(m°C), two layers 50 mm thick.

In the calculations, the width of the roadbed is conventionally taken as 6.0 m.

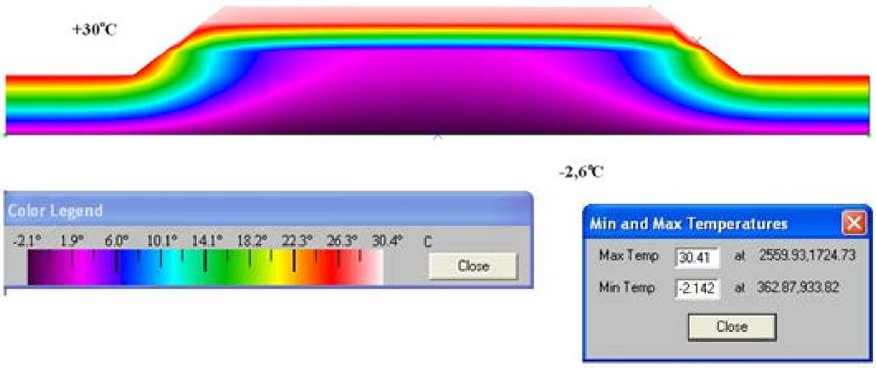

Figure 6. Temperature distribution in a road structure filled with foam glass gravel at an outside air temperature of +30 °C (permafrost, protection against thawing).

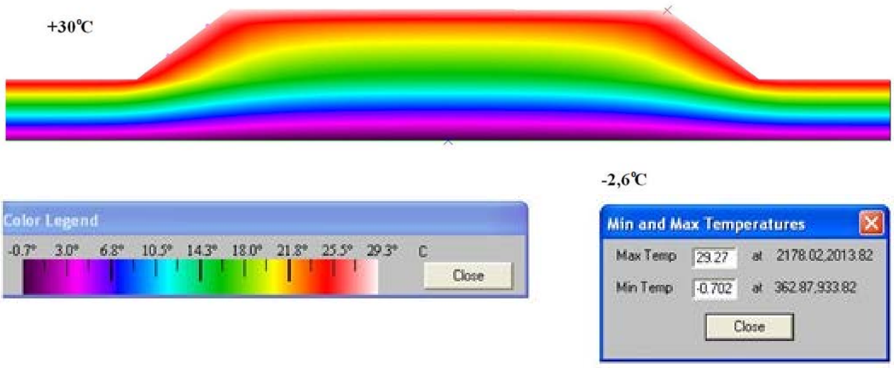

Figure 7. Temperature distribution in a road structure without foam glass gravel filling at an outside air temperature of +30 °C (permafrost, protection against thawing).

When assessing the insulation system using foam glass gravel for frost protection, the following boundary conditions were taken. Soil temperature is 4 °C; the temperature of the outside air in the calculation is taken: minus 30 °C.

Layers of the road structure filled with foam glass gravel: peat soil with a density of 400 kg/m^3; thermal conductivity coefficient of 1.39 W/(m°C); sand embankment with a density of 1400 kg/m^3, thermal conductivity coefficient of 2.48 W/(m°C), layer thickness of 400 mm; filling with foam glass gravel with a density of 140 kg/m^3, thermal conductivity coefficient of 0.085 W/(m°C), layer thickness of 250 mm (according to research data); asphalt concrete with a density of 2100 kg/m^3, thermal conductivity coefficient of 1.05 W/(m°C), two layers 50 mm thick.

Layers of the road structure without foam glass gravel filling: peat soil with a dry density of 400 kg/m^3; thermal conductivity coefficient of 1.39 W/(m°C); sand embankment with a density of 1400 kg/m^3, thermal conductivity coefficient of 2.48 W/(m°C), layer thickness of 650 mm; asphalt concrete with a density of 2100 kg/m^3, thermal conductivity coefficient of 1.05 W/(m°C), two layers 50 mm thick.

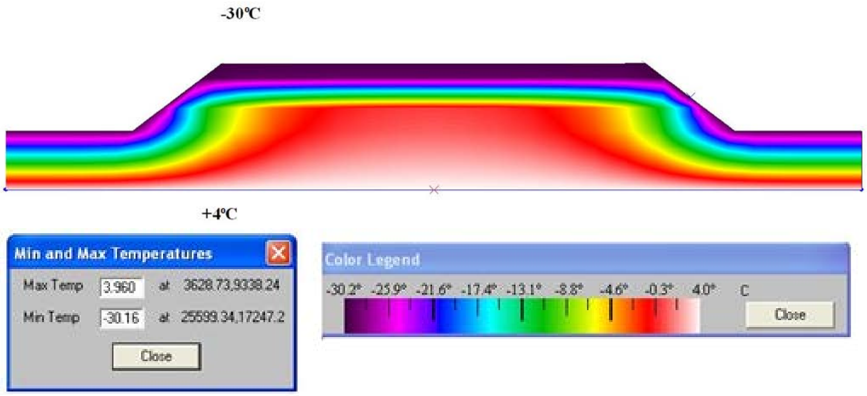

Figure 8. Temperature distribution in a road structure filled with foam glass gravel at an outside air temperature of minus 30 °C (heaving soil, frost protection).

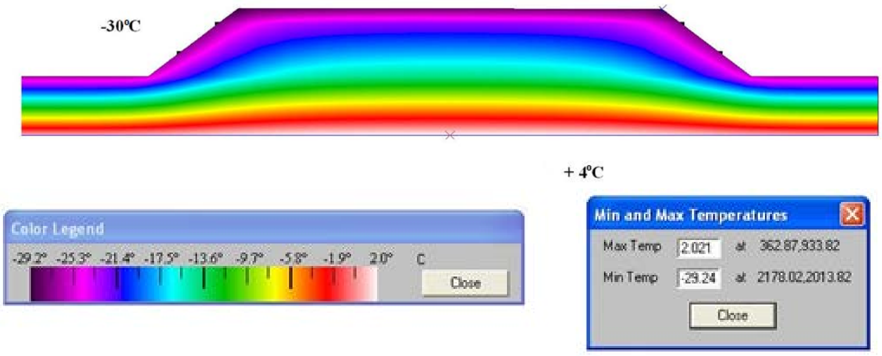

Figure 9. Temperature distribution in a road structure without foam glass gravel filling at an outside air temperature of minus 30 °C (heaving soil, frost protection).

The modeled distribution of temperature fields (Fig. 6, 7) shows that the filling with foam glass gravel allows keeping the permafrost soil from thawing while maintaining positive temperatures in the upper part of the embankment. On problematic bases (heaving sections of highways), in order to reduce the freezing depth to permissible norms and to exclude frost heaving processes in the soil of the embankment and natural base, thermal insulation layers are laid in the bases of pavements and under the ballast (Fig. 8, 9).

Preliminary calculations of the distribution of temperature fields at the base of a conditional road structure on permafrost soils with an insulating layer of foam glass gravel have been carried out. Calculations of real structures must be carried out taking into account the conditions of the construction and climatic zone of construction according to Russian Construction Norms SP131.13330.2012.

Modeling and calculation of temperature fields using the THERM program for structures of various types made it possible to simulate their freezing regime. Freezing simulations on models showed that the freezing depth in a road structure with an insulation layer of coarse sand with thickness of 0.3 m is 2.6 m. The use in a similar road construction with a thermal insulation layer of foam glass gravel with thickness of 0.25 m allows to limit the frost depth to 0.2 m.

Analysis of the use of road structures with thermal insulation from foam glass gravel and the results of modeling thermal fields in insulation systems showed that the construction of road bases with such thermal insulation allows to obtain functionally realizable structures with high durability. This is especially true for the construction of a roadbed on problem soils – permafrost and heaving.

4. Conclusions

Foam glass gravel, which is confirmed by the results of the experiment, in terms of strength and thermophysical characteristics, fully meets the requirements for heat-insulating materials used in road systems when laying a roadway on problem soils. The strength of foam glass gravel, depending on its degree of compaction (from 10 to 50 %), is in the range of 0.90 ... 1.58 MPa, and the thermal conductivity coefficient is from 0.087 to 0.099 W/(m °C), water absorption of gravel by volume does not exceed 1.8 %, and sorption humidity (at a relative air humidity of 98 %) does not exceed 4.2 %.

Calculation of temperature fields using the THERM program in structures of various types made it possible to simulate their freezing regime. The efficiency of using foam glass gravel backfill is shown both for protection against soil freezing and for protection against thawing of permafrost soil. As a result of calculations, it was found that the use of heat-insulating backfill of foam glass gravel with a thickness of 0.25 m makes it possible to protect the permafrost soil of the road base from thawing for the considered conditions of the first road-climatic zone. At the same time, the imitation of freezing on models (for the considered boundary conditions) showed that the use of a heat-insulating layer of foam glass gravel with a thickness of 0.25 m in the road structure makes it possible to limit the freezing depth to 0.2 m, versus 2.6 m without heat-insulating layer.

The experience of using road structures with thermal insulation from foam glass gravel has shown that the implementation of these systems makes it possible to obtain functionally realizable structures with high durability. This is especially true for the construction of the roadbed on problem soils.

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Contacts:

Vyacheslav Semenov, science-isa@yandex.ru
Igor Bessonov, ca2so42h2o@rambler.ru
Aleksey Zhukov, lj211@yandex.ru
Elizaveta Mednikova, lisamednikova97@gmail.com
Ilya Govryakov, govr190@mail.ru

Received 03.06.2020. Approved after reviewing 24.08.2021. Accepted 06.09.2021.