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Key words: *temperature, thermal conductivity, mixtures, structural design, permafrost zone, road pavement, thermal insulation, thermal resistance, energy efficiency, foam glass aggregate*

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THERMAL PROTECTION OF ROADS IN THE PERMAFROST ZONE

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The problem of choosing a method of construction of thermal protection layer of the road pavement in permafrost zone was solved. Simple engineering formulas to justify the choice of the specific type of thermal insulation structure were obtained. It was determined that a structure composed of two layers (separate layers insulant and of sand) is always more efficient than a thermal insulation mixture (combined insulant and sand) applied in one layer for the purposes of maximizing thermal resistance. At the same time, a quantitative assessment demonstrated that in many practical cases, the difference in thermal resistance of the two kinds of structures is slight and is within the margins of permissible precision of engineering calculations. For this reason, it is expedient to also consider the technological demands of application of one or the other type of thermal insulation layer in addition to the thermal resistance considerations. Formulas to find the area of rational use of thermal insulation mixtures instead of merely sand bedding were devised. It was determined that the thickness of bedding in one or the other case is significantly dependent on the ratio of thermal conductivity coefficients of sand and the insulant. In addition, the change in relative thickness of the layer can have both negative and positive values.

Key words: temperature, thermal conductivity, mixtures, structural design, permafrost zone, road pavement, thermal insulation, thermal resistance, energy efficiency, foam glass aggregate

INTRODUCTION

Protection of engineering structures from cryogenic impacts is a current problem both in Russia and abroad. Cryogenic phenomena and processes, such as gradual thawing of rocks, solifluction, cavern formation, soil swelling, soil cracking due to freeze, are causing significant complications for construction and exploitation of both surface and underground engineering structures [1, 2, 3]. The scientific and engineering communities are devoting significant attention to research and development of methods of protecting linear structures from cryogenic impacts [4, 5, 6]. Linear structures such as railroads and auto roads occupy a special place in this effort because they are crucial components of infrastructure securing reliable operation of industrial enterprises strategically important for the regions and the country. Many scientific works were dedicated to studying impacts of the thermal factor on the reliability of roads and to development of new methods and means of protecting roads and other infrastructure components from negative cryogenic influences [7, 8, 9]. However, there is still space for advancing in this area. For now, no universally reliable methods of decreasing the negative impacts of cryogenic processes on the engineering structures, in particular, roads, were found. And it is possible that, considering the diversity of climatic and geocryological conditions of the permafrost zone of Russia, no such universal method may exist. However, solving the problem of finding efficient methods of protecting the road pavement in permafrost zones is interesting from the point of view of both practice and science. Specifically, it is known that use of thermal protection materials in road pavements allows to significantly increase the reliability of the roads and prolong the exploitation time between repairs [10, 11, 12]. The aim of the present work was to solve two specific problems in the area of design of thermal insulation layers for roads in the permafrost zone. The first problem: to assess the efficiency of a single-layer thermal insulation consisting of a mixture (sand and insulant) in comparison with a two layer thermal insulation structure (separate layer of sand and a layer of insulant). Second problem: to determine the efficiency of use of thermal insulation mixtures in comparison with use of mere sand beddings, but of a greater thickness. The economic indicators were not considered at this stage. That is, it is assumed that the cost of sand and the insulant is more or less the same. In practice this may be the case when natural materials (for example, burnt rocks) or residuals from industry (for example, slag) are used. In order to determine the area of economic efficiency of use of thermal insulation mixtures it is necessary to solve the problem similar to the one solved in the work [13, 14], which considers use of various techniques to reduce permafrost degradation to achieve reduction in cost of repairs.

MATERIALS AND METHODS

In order to solve the first problem, the target formula can be written in the form

$$F = R_1 - R_0$$

Where R_0 is the thermal resistance of the layer of the sand and insulant mixture, m²K/W; R_1 is the thermal

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resistance of the two layer structure, m²K/W. The meanings of these parameters can be found from the following formulas:

$$R_0 = \delta_0/\lambda_0$$

$$R_1 = \frac{\delta_1}{\lambda_1} + \frac{\delta_2}{\lambda_2}$$

Where δ_0 is thickness of the insulant and sand mixture layer, m; δ_1 is thickness of the sand layer, m; δ_2 is thickness of the insulant layer, m; λ_1 is thermal conductivity coefficient of sand, W/mK; λ_0 is thermal conductivity coefficient of the sand and insulant mixture, W/mK. The parameter λ_0 can be determined using the Schwerdtfeger formula [15]:

$$\lambda_0 = \lambda_1 \cdot f$$

$$f = \{\frac{[1 + 0,5\eta - m(1-\eta)]}{1 + 0,5\eta + 0,5m(1-\eta)}\}$$

$$m = \delta_2/\delta_0$$

$$\eta = \lambda_0/\lambda_1$$

Considering that $\delta_0 = \delta_1 + \delta_2$, the final formula for the analysis of the target function will take the following form:

$$F = 1 + m\left(1 - \frac{1}{\eta}\right) - 1/f$$

If the target function is positive, the two layer structure of the insulation will be more efficient than a single layer structure. If the target function is negative, the opposite will be the case. A change in thermal resistance when the two layer structure of sand and thermal insulant is replaced with a mixture of sand with insulant can be found according to the formulas (7) and (8)

$$e = \left|\left(\frac{R_1}{R_0} - 1\right)\right| \cdot 100\%$$

$$\frac{R_1}{R_0} = \left(1 - m + \frac{m}{\eta}\right) \cdot f$$

If the change does not exceed the deviations permitted in engineering practice (as a rule, 10%), only the technological criteria should be considered when choosing the thermal insulation structure. For example, criteria such as how difficult and fast it is to build the thermal insulation structure and the resilience characteristics of the thermal insulant etc. For the solution of the second problem, the target function which should be analyzed can be written in the form similar to equation (1)

$$F = R_1 - R_2$$

Where R_1 is thermal resistance of the sand layer, m²K/W; R_2 is thermal resistance of a layer of thermal insulation mixture, m²K/W. The values of these parameters can be found from following formulas

$$R = \sum_{i=1}^{n} \frac{\delta_i}{\lambda_i}$$

$$\delta_2 = \frac{\delta_1}{\lambda_1} \cdot \lambda_2$$

Where δ_1,δ_2 is thickness of the layer of sand and insulant mixture, m; λ_1, λ_2 is thermal conductivity coefficient of sand and the thermal insulation mixture, W/mK. The parameter λ_2 can be determined using the Schwerdtfeger formula [15]. If the target function (1) is positive, there is no need to use the thermal insulation mixture. A sand bedding is sufficient. If the target function is negative then the opposite applies, it is expedient to replace the sand bedding with a bedding made of thermal insulation mixture. A parameter β which characterizes the relative change in thickness of the bedding when thermal insulation mixture is used instead of sand. That is, $\beta = (\delta_1 - \delta_2) / \delta_1$. This parameter can have both positive and negative values. The latter is possible when the thermal conductivity coefficient of the mixture is higher than the thermal conductivity coefficient of sand. After a few uncomplicated transformations it is possible to determine that the parameter β can be found from the formula:

$$\beta = \left(1 - \frac{\lambda_2}{\lambda_1}\right) \cdot 100\%$$

RESULTS

Numerical analysis of the factors in the formula (6) shows that the value of the parameter ($1/f$)is bigger than 1. Simultaneously, the value of the term $m\cdot(1-1/\eta)$ is always bigger than the value of ($1-1/f$). For this reason, the target function F is always positive. This means that the two layer thermal insulation structure is always more efficient in terms of thermal resistance compared to the single layer base structure composed of a mixture of sand and insulant. This is the case from the theoretical point of view. From the practical perspective, the quantitative difference of thermal resistance, that is, the quantitative difference of the values of the target function of the two kinds of thermal insulation structures matters. If the difference does not exceed the level of imprecision permitted in engineering calculations (usually 10%), it is necessary to decide which method of insulation to choose based on the technological factors rather than thermal criteria. In addition, some efficient insulants, such as non-polystyrene granules, cannot be used as a separate insulant layer because of their low strength and creasing.

DISCUSSION

Results of variant calculations of the target function are presented in the form of charts in the figures. Fig. 1 shows the change of target function depending on the relation of the thermal conductivity coefficients of the insulant and sand (parameter η) with different concentrations of the insulant in the mixture (parameter m). From the charts it is visible that the lower the parameter η and the higher is the parameter m, the higher is the value of the target function. That is, the lower is the thermal conductivity coefficient of the insulant and the higher the insulant's concentration in the mixture, the more efficient is the two layer structure of thermal insulation layer compared to the single layer structure. With increase in the thermal conductivity coefficient of the insulant or decrease of the thermal conductivity coefficient of sand (for example, through prior drying), that is, with increase of the parameter η, the role of the concentration of the insulant in the mixture decreases – at the concentration of 0.3, the curves in the figure are virtually merging. In addition, the value of the target function approaches zero and there is no practical purpose in constructing a two layer thermal insulation structure in this area of values of the parameters.

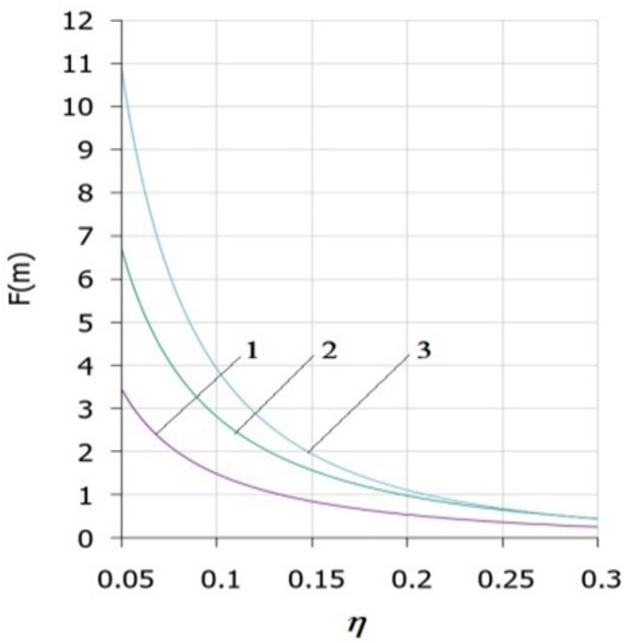

Figure 1: Change in the target function depending on the parameter η with different concentrations of m insulant in the mixture: 1-0.2; 2 – 0.4; 3 – 0.8;

This can be seen well on the 3D chart in figure 2. The figure 2 is showing the change of the target function depending on the parameter η with different concentrations of the insulant in the mixture. For example, when the value of the parameter η is 0.4 it is visible that the lower part of the plane is nearly parallel to the axis m. That is, the concentration of the insulant in the mixture has no influence on the final result. The upper part, on the other hand, with the value of the parameter η being 0.1, has a highly visible curved shape, which points to a significant dependence of the concentration of insulant in the mixture on the choice of technical solution for the thermal insulation layer structure. The higher the concentration,

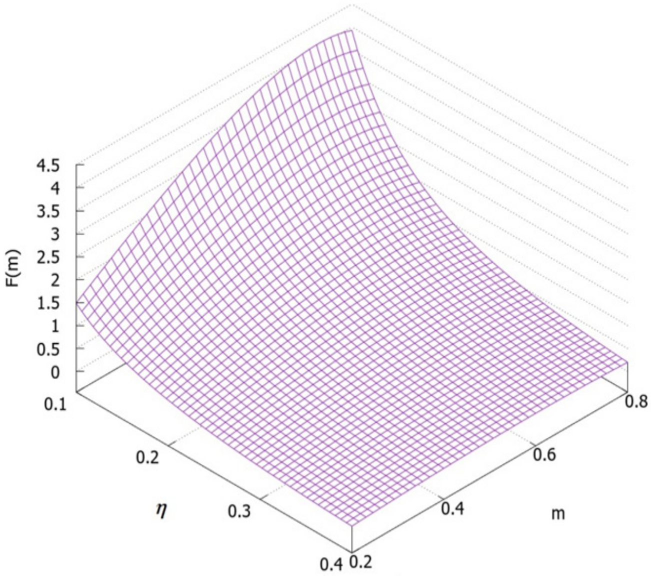

Figure 2: Change in the target function depending on the parameter η with different concentrations m of the insulant in the mixture

the higher the dependence. The target function with the concentration of insulant 0.2 has a value of 1.5. When the concentration of the insulant is equal to 0.8, the value of the target function is equal to 4.0. That is, it almost 2.7 times higher. The chart below shows that there is an effective area of relations of the parameters η and m in which the considered task is relevant. In order to determine the area, formulas (7) and (8) can be used. The results of the calculation are represented in the form of charts in the figure 3 and figure 4.

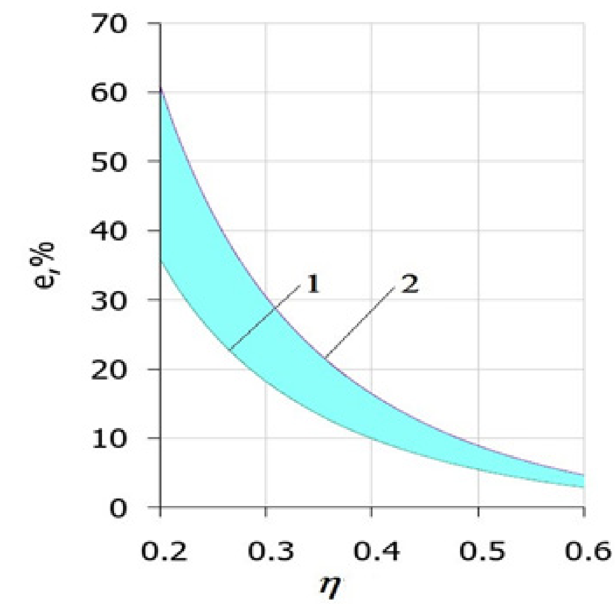

Figure 3: The change of thermal resistance when a mixture instead of layered structure of thermal insulation is used with different concentrations of the insulant in the mixture: 1 – 0.8; 2 – 0.4;

In the figure 3, the area of change in thermal resistance (increase in %) of the layered structure of thermal insulation layer when the concentration of the insulant in the mixture changes from 0.4 to 0.8 is filled. If the engineering principle that at most 10% change is permitted is followed, this area is delimited by the values of the parameter η 0.4 – 0.48. This is clearly visible in the figure 4, where the 3D chart of dependence of increase of thermal resistance of the structure using the layered method instead of the single layer method of thermal insulation.

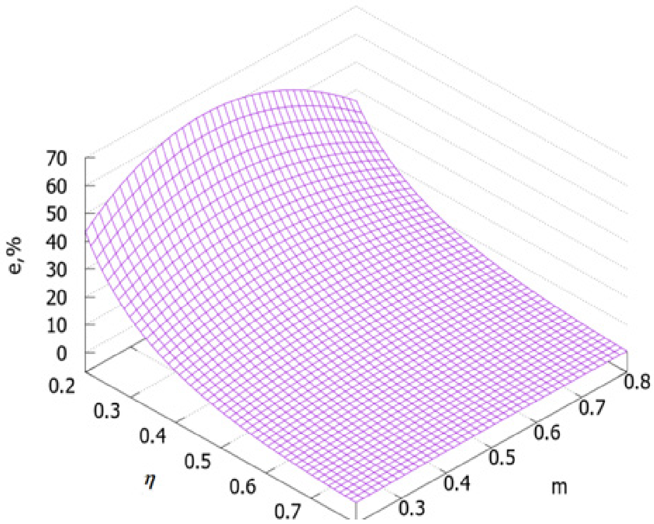

Figure 4: The change in thermal resistance of the structure when the layered method of application of sand and insulant is used

From the figure it is visible that the upper part of the plane has a clearly curved shape, while the lower part represents a straight line. That is, as was mentioned above, the concentration of the insulant when the parameter η exceeds 0.48 does not influence the thermal insulation structure as the increase of thermal resistance will not be higher than 10%. The results of the solution of the second task are presented in the form of a 3D chart in the figure 5. The X axis represents the thickness of the sand bedding, the axis Y represents the fraction of the insulant material in the mixture which determines the value of the coefficient of thermal conductivity coefficient of the thermal insulation mixture - λ_2. As can be seen in the chart, there is both a positive and a negative area of the change of the parameter β. The latter means that a given concentration of the thermal insulant in the mixture and a value of the thermal conductivity coefficient of the mixture, the thermal insulation layer will increase compared to a regular sand bedding. That is, application of a thermal insulation mixture is not expedient. It needs to be noted that this area (denoted blue in the figure) is not very large. Nevertheless, when designing road pavements with thermal insulation in the permafrost zone it is necessary to consider the expedience of use of thermal insulation mixtures according to the methodology developed.

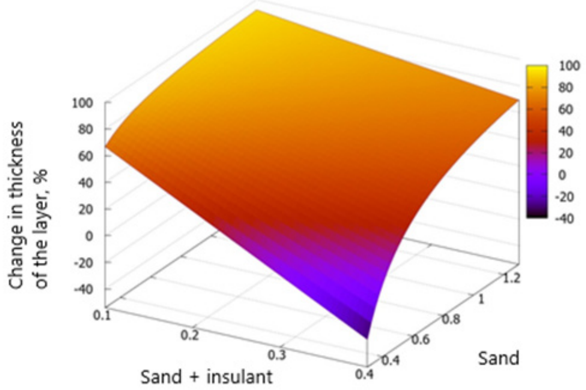

Figure 5: Change in thickness of thermal insulation bedding compared to sand bedding

CONCLUSIONS

The problem of choosing a method of construction of thermal protection layer of the road pavement in permafrost zones was solved. Simple engineering formulas to justify the choice of the type of thermal insulation structure were obtained. It was determined that, from the perspective of maximizing thermal resistance, a structure composed of two layers (a layer of insulant and a layer of sand) is always more efficient than a thermal insulation mixture (mixed insulant and sand) consisting of one layer. At the same time, the quantitative assessment demonstrated that in many cases relevant for practical application, the difference in the values of thermal resistance of the two types of structures is not very large and is within the boundaries of the permissible precision of engineering calculations. For this reason, it is expedient to also consider the technological demands of creating one or the other type of thermal insulation layer, in addition to the thermal resistance calculations. Formulas to find the area of rational use of thermal insulation mixtures (sand and thermal insulation materials) instead of merely sand bedding were devised. It was determined that the thickness of bedding in one or the other case is significantly dependent on the ratio of thermal conductivity coefficients of the sand and the insulant. In addition, the change in relative thickness of the layer can have both negative and positive values.

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