MULTIFACTORIAL APPROACH TO THE DETERMINATION OF HEAT TRANSFER IN MULTILAYER SURFACES

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Development of the territories with specific climatic conditions requires the selection of effective materials. Multilayer composite materials are suitable for these purposes in road construction in the Arctic. The article presents a design scheme for a multilayer road surface, which is used to determine the collection of traffic loads. The method of solving the inverse Cauchy problem and the empirical formula to determine the value of the temperature arising from deformation at the contact point of the surface of a multilayer road surface and transport are determined. The experimental studies conducted were aimed to determine the heat transfer through a three-layer road surface made of structural foam concrete of the D1200 brand. The processing of experimental data on temperature values made it possible to derive the formula to determine the change in the layers' temperature depending on their number.

KEYWORDS

multilayer surfaces, composite, heat transfer, arctic, concrete, road

1 INTRODUCTION

Choice of an effective material is one of the most important aspects of construction. It is essential for the material to meet the specified requirements, to be wear-resistant, and to have minimal effect on the external environment [Cachova 2018].

In April 2021, the unified action plan for the implementation of the Fundamentals of the State Policy of the Russian Federation in the Arctic was updated and the Strategies for the Development of the Arctic Zone of the Russian Federation and Ensuring National Security for the period up to 2035 were approved by the Decree of the Government of the Russian Federation No. 996-r of April 15, 2021. Similar documents – the Arctic strategies, were previously adopted and updated by Denmark, Canada, USA, Norway and a number of other interested countries.

For more than ten years, the development of the Arctic has been designated at the highest level as a priority task of economic development and ensuring national security for the participating countries and observers of the Arctic Council.

Over the years in Russia a regulatory framework has been created and a number of major projects have been implemented for the development of the region. But despite of the certain success of the policy of the past years in the Russian Arctic, there are still a number of unsolved problems and challenges of a socio-economic nature. The most acute of them is the low level of development of transport, information and communication infrastructures [Karaganov 2021]. By 2025, in the Russian Arctic, it is planned to reconstruct sections of the Syktyvkar – Ukhta – Pechora – Usinsk – Naryan-Mar highway and to construct Naryan-Mar – Usinsk, Kolyma – Omsukchan – Omolon – Anadyr roads.

The Arctic is characterized by harsh and changeable climatic conditions: high dynamics of weather changes, year-round negative temperatures, strong winds and snowstorms, scant precipitation, multi-meter ice cover [Streletskiy 2015]. Therefore, multilayer structural composite materials are suitable for construction of road surfaces in these conditions [Pogrebnjak 2017]. It is also necessary to know the processes occurring due to heat transfer.

Several authors conducted a research in heat transfer through the concrete [Guo 2011, Yuen 2007, Brodnianska 2018, Babiarz 2020, Fogiatto 2019]. The data obtained make it possible to apply them on practice and develop durable concrete surfaces for specific operating conditions.

This paper presents a study aimed to research the heat transfer of multilayer concrete, suitable for road construction in the Arctic's conditions.

2 ANALYSIS OF THE PROBLEM

Currently, implementing the principles of the Industry 4.0, it is necessary to present a multilayer composite in a form of a complex technical system, as it's shown in the Fig. 1. Its research should be carried out using a multifactorial approach, which makes it possible to identify the regularities of the functioning and development of such systems under the influence of external factors [Pivarciova 2019a]. This makes it possible to formalize a mathematical model close to reality, to carry out a huge number of computational experiments, to evaluate the expected results of changes in the state of the material, and to choose the theoretically optimal solution to the problem of obtaining the required composite for road surfaces.

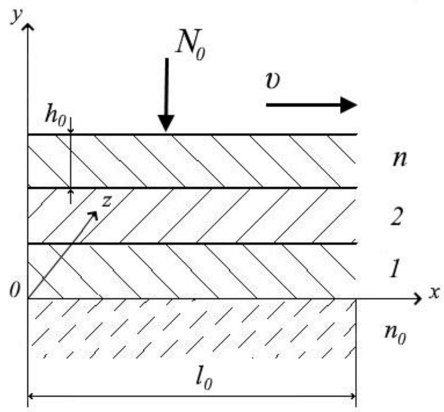

Figure 1. Design scheme of a multilayer composite road surface: n – number of layers of the road surface (the last layer n_0 is the soil with a temperature $T_0 < 0$ºC); h_0 – thickness of the layers (assumed to be the same); N_0 – traffic load; υ – vehicle speed; l_0 – length of the contact area; b_0 – width of the contact area

The load N_0 is carried out by transport at the speed υ (cars, trucks, tractors, etc.) on wheels-tires under pressure. It is transmitted to the road surface through the area: $\Omega_0 = l_0 \cdot b_0$. The value of the load N_0 is considered to be set as the average for the transport system or specific for a certain type of machines and mechanisms.

During functioning in the complex systems, such as multilayer composite road surface, the state, structure and main indicators are changing. In addition, the specificity of the implementation of the results of the operation of such systems is dependent and changes during operation due to changes in environmental conditions, requirements of industrial production, science and the market, as well as places of application of the final product. These transformations often take place suddenly, but not in a regular and planned way.

For responsible complex systems, the way out is as follows: when taking into account the influencing factors, it is necessary to know their possible connection, i.e. mutual influence in certain situations. Identification and assessment of the interaction of factors are decisive for obtaining multivariate mathematical models, and the construction of these relationships as functions is the main task of obtaining a high-quality composite material [Bazhenov 2012].

Under the action of the load N_0, elastic deformation (compression) of layer *n* occurs on the site Ω_0. For layers 1 and 2 the same load is insignificant, since it is already distributed over the full area of the layers. The strain rate at the site Ω_0 is determined experimentally, but it is obvious that this speed will be less than the speed of sound:

$$\upsilon_s = \sqrt{\frac{E_m}{\rho_m}}, \qquad (1)$$

where E_m and ρ_m are the elastic modulus and density of the layer material, respectively.

The situation with the deformation energy of the layers is similar. The energy expended on the deformation can be determined as:

$$E_{def} = \Delta h_0 \cdot N_0 \cdot t_{load}, \qquad (2)$$

where $\Delta h_0 = \upsilon_{def} \cdot t_{load}$ – depth (amount) of the deformation; $t_{load} = \frac{l_0}{\upsilon}$ – load time; υ_{def} – strain propagation rate.

This energy is spent on overcoming the compression resistance and heating of the layer material.

Assume that overcoming the compressive resistance (i.e. overcoming internal friction) also turns into heat. Then the entire deformation energy E_{def} can be taken as thermal energy applied to the layer *n*. We suppose that the maximum deformation of the layer occurs in the first seconds. The deformation is transmitted to the surface of the multilayer material through a small area of contact of the transport wheels with the surface of the layer. For subsequent layers, the deformation extends to their entire area. Then we determine the initial heating temperature of the material of the layer *n* at the contact surface point from the value of thermal energy. This will be the moving heat source. To determine its parameters, we take the source as an unbounded plate and solve the Fourier problem with constraints. We determine the temperature on the surface of the base-layer n_0 by the maximum heating temperature, the thermal conductivity of the layer material and its known characteristics as time, area of action of the load and initial temperature. And, if this temperature is higher than the melting temperature of the base-layer material n_0 (i.e., water trapped in permafrost soil), then it is possible to determine the amount of thawed water and the subsequent time of its freezing. According to this time, the permissible intensity *q* of the vehicle on this roadway is determined:

$$q = \frac{E_{def} + E_{heat}}{\Omega_0}. \qquad (3)$$

The initial Fourier heat equation has the form [Liu 1990]:

$$\frac{\partial \theta}{\partial T} = \alpha \cdot \nabla^2 \theta, \qquad (4)$$

where $\nabla^2 = \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}\right)$ – Laplace operator; $\alpha = \frac{\lambda}{C \cdot \rho}$ – coefficient of thermal diffusivity; $\lambda = \lambda_0\left[1 + A_T(\theta - \theta_0)\right]$; λ_0 – coefficient of thermal conductivity of the layer material at the temperature θ_0, ºC; A_T – temperature coefficient determined from tables [Nashchokin 1975]; *C* – mass heat capacity; *ρ* – layer material density.

The differential equation of thermal conductivity (4) allows us to determine the temperature depending on time and coordinates at any point of the heating surface. To solve the problem, it is necessary to take into account the initial and boundary conditions [Repko 2005, Lu 2015]:

- the initial condition $\theta(x, y, z, T_н) = \theta_0$ is specified as the temperature distribution inside the investigated area on the layer surface at the initial moment of time $T_i = 0$;

- Newton's boundary conditions specify heat transfer at the boundary of the layer surface with the environment:

$$q = \alpha_0(\theta_0 - \theta_{amb}), \qquad (5)$$

where α_0 – heat transfer coefficient of the layer material; θ_0 – temperature at the surface of the layer; θ_{amb} – ambient temperature.

Parameters in the conditions (4)-(5) depend on time *T*. In this case, we solve the one-dimensional Fourier heat conduction problem. This is a fairly close to real model of the deformation process of multilayer materials. When the source moves infinitely long, then the maximum value of the field temperature is determined by the formula:

$$\theta = \frac{2q\alpha}{\pi\lambda\upsilon}\int_{Z-H}^{Z+H} \exp(-\xi)\cdot K_0\left(\sqrt{X^2+\xi^2}\right)d\xi, \qquad (6)$$

where $\xi = \frac{\upsilon(z - z_i)}{2\alpha}$; $X = \frac{\upsilon \cdot x}{2\alpha}$; $Z = \frac{\upsilon \cdot z}{2\alpha}$; $H = \frac{\upsilon \cdot h}{2\alpha}$; υ – the speed of movement of the heat source, i.e. vehicle speed; $K_0(m_\delta) = \int_0^\infty \frac{dg_\delta}{g_\delta}\exp\left[-\left(m_g^2 g_\delta^2 + \frac{1}{4g_\delta^2}\right)\right]$ – integral representation of the modified zero-order Bessel function of the second kind; $g_\delta = \xi\frac{4\alpha^2}{\upsilon^2 r^2}$; $m_\delta = \frac{\upsilon \cdot r}{2\alpha}$; $r^2 = (x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2$; *(x, y, z)* – coordinates of the points of the deformation area; (x_i, y_i, z_i) – coordinates of the points of instant heat release *q*.

This approach in constructing the direct Cauchy problem was used in the thesis [Repko 2005] to determine the heating of the part from the heat generated during grinding. It is known and widespread for solving problems in the field of mechanical engineering [Kalinin 1990, Sipailov 1978]. We used the equation (6), assuming that the heating value is known, thereby turning the direct Cauchy problem into the inverse, but applied to road construction structures.

The initial temperatures θ_0 must be determined on all layers of the road surface, ending with the lower one directly touching the ground. The heat flux is partially reflected from each facet, thereby reducing the flux density. And, if the thermal conductivity of the layers is considered constant, due to the reflection and absorption of heat, the heating of the upper layer increases, as much as the heat capacity allows it. This occurs until the temperature at all points of the layer material is equal to the heating temperature. This is beneficial for road surfaces in the Arctic, because it takes longer for all layers to warm up. By changing the intensity of traffic, it is possible to regulate the heat transfer between the layers so that the heating will not reach the ground, and cooling to the ambient temperature will begin during a break in traffic.

The law of surface temperature variation can be found experimentally. To do this, it is necessary to select the points of the layer *n*, measure their temperature, and formalize the curve in the form of a power polynomial, by the solution of which it is possible to find the temperatures and thermal conductivity of the entire multilayer coating. This final temperature will be the maximum for the task at hand. Then, we can calculate any parameter from the equation (6) by temperature. This will be the inverse Fourier problem.

The solution of this problem is possible using the method of targeted enumeration, which is a special case of lexicographic optimization. It assumes that some heating factors are known or set. In the direct problem, the search for unknown extrema of these factors is a priority. The solution of the inverse problem will not be the only one, but it determines the range of acceptable values.

3 MATERIALS AND METHODS

To conduct experimental studies, models of elements of a three-layer road surface made of structural foam concrete of the brand D1200 were designed and manufactured (λ = 0,35 *W/m·K*) [Pivarciova 2019b] with dimensions 100×100×25 *mm* of a layer. Thermocouples were installed in micro gaps between layers.

The number of experiments was calculated according to the theory of experiment planning, proceeding from obtaining the required accuracy of statistical data values.

An experimental equipment (Fig. 2) was used to obtain experimental data.

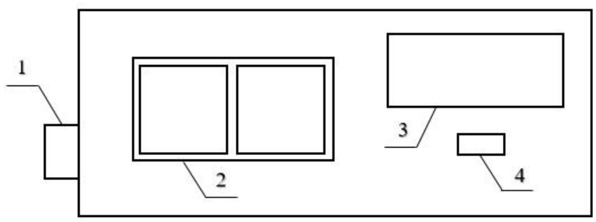

Figure 2. Scheme of the experimental equipment: 1 – connection module; 2 – multilayer prototypes; 3 – layer temperature meters TRM-200; 4 – controller-monitor KMC-F1

The experimental equipment is a stand with test samples with thermocouples attached to them. A heating element is located at the base of the equipment. An electric heater (t = 130 ºC) is placed on the side of the inner surface of the samples. It provides heating for specific periods of time.

The temperature of the surfaces of the tested samples is measured by thermocouples in micro-gaps between the layers using TRM-200 meters, which show the temperature of the upper and lower parts of each layer of the test sample. The amount of heat transferred from the heater to the samples, i.e. the heat flux, is recorded by the monitor controller KMC-F1. The equipment is also provided with a connection module and automation to control the process parameters.

4 RESULTS AND DISCUSSION

The results of experimental studies are presented in Fig. 3. The temperatures of the lower and upper surfaces of the sample layers were recorded every 30 seconds for 20 minutes. The processing of these data made it possible to determine the nature of the heating of the layers.

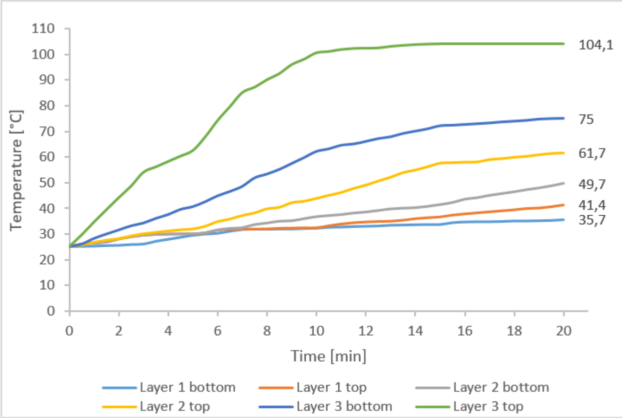

Figure 3. The results of experimental studies in the form of a graph of the temperature distribution over the layers in time

As it is shown in graph in Fig. 3, a stable surface temperature of the Layer3 top was reached already after 12 minutes. At the Layer3-Layer2 interface, this took effect only after 16 minutes, while the temperatures at the Layer2-Layer1 interface and at the Layer1 bot temperature layer remained low, and slowly rising. This means that the observed layers provide sufficient thermal resistance to heating.

In Fig. 4 the courses of temperature changes in individual layers are shown.

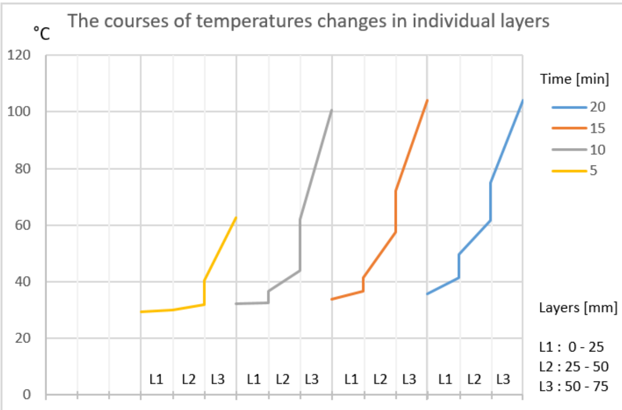

Figure 4. The courses of temperatures changes in individual layers

The individual temperature curves in the layers in Figure 4 show an interesting phenomenon of abrupt changes of measured temperatures at interfaces of individual layers. This is due to several factors. For example, a big impact in this has the fact that the individual layers of the subsoil are not perfectly connected, and a thin layer is formed at their interface. This hinders the heat spreading process significantly. The continuity of heat conduction through the individual layers is interrupted. The resulting differences may be partly due to the inaccurate placement of temperature sensors on the surface of the tested layers.

Comparing the values of temperature indicators on different layers of foam concrete, we constructed a curve of temperature changes in the road surface depending on the number of layers (Fig. 5).

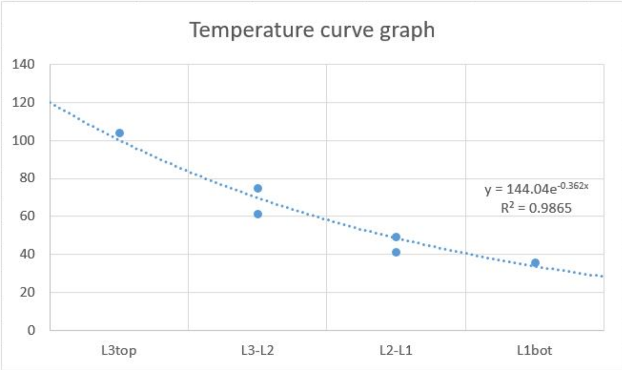

Figure 5. Temperature curve graph on the outer surface of the layers

After evaluation of the measured temperatures of surfaces of the samples at the end of the 20 minutes' experiment, a temperature curve graph was evaluated to determine representative values. This shows the exponential course of temperature decrease from the point of heat load to the last layer. To analytically express this dependence, calculation was done by:

$$t = a.\exp(b.n). \quad (7)$$

where t – expected heating temperature, °C; n – number of layers of foam concrete necessary for temperature measurement; a, b – constants.

For specific experimental results, the values of the constants were determined:

a = 144.04;

b = –0.362.

The thickness of the surface in 5 layers is accepted conditionally as the most common in road construction.

The exact graph of the equation (7) shows the bends and changes in the points of abutment of the layers to each other.

The empirical dependence (7) includes approximate data on calculating the number of layers in dependence on temperatures occurring on the surface. Both equations (6)-(7) need to be clarified in practice. In particular, the formula (6) is in the field of road construction.

In the future, it is necessary to determine experimental studies to determine the values of thermal contact resistance between the individual layers depending on time. It also is necessary to conduct a study of transient processes during heat transfer between layers. This will also lead to an expansion of the range of composite materials used.

5 CONCLUSION

Reconstruction of highway sections is planned in the Russian Arctic by 2025. In these purposes multilayer structural composite materials can be used. Therefore, it is necessary to know the processes arising from heat transfer [Janacova 2013] and developing new materials [Sviatskii 2019].

The demand for multilayer composite materials in the Arctic is due to the harsh climatic conditions and increased requirements for the quality of road surfaces in high latitudes. But with all the advantages, such as excellent physical and mechanical characteristics, low thermal conductivity, high chemical and corrosion resistance, etc., the applicability of multilayer composites in Arctic road construction is still questionable.

The article defines a method for solving the inverse Cauchy problem and builds an empirical formula for determining the value of the temperature that occurs during deformation at the contact point of the surface of a multilayer road surface and transport. This is a mathematical interpretation of the process of heat transfer through the road surface, which is presented in the form of a non-stationary Fourier problem. The solution of the problem is sought by the method of multifactorial lexicographic optimization taking into account the temperatures arising in the layers and is easily possible with the use of a computer. This allows to determine the optimal number of surface layers, their thickness and material. In the future the described method may contribute to improving the efficiency of multilayer surfaces, heat transfer or concrete application.

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