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METHOD OF THERMAL CALCULATION OF HEATING ROAD COVERING

Safe maintenance of roads, especially in the winter, is a topical issue today. Among the various traditional methods of combating snow and ice on the coating, there is an alternative method, in particular the use of heating coatings. The method of thermal calculation of ecologically safe heating road surface is developed, namely – the problem of thermal conductivity at the set certain thermal boundary conditions and conditions of contact of layers is solved. The heating system of the coating consists of crushed stone-mastic asphalt concrete, a layer of electrically conductive concrete (fibroconcrete), carbon mesh for power supply and a layer of thermal insulation. To solve the thermal problem, we used the hypothesis of temperature distribution in the layers of the heating coating over the thickness of the system. Physico-mechanical and thermophysical characteristics of layers and boundary conditions on their surface are given. A heat flow of a given power acts through the lower surface. Heat transfer occurs from the lower surface to the upper – perpendicular to the package of layers, which makes the problem of heat transfer one-dimensional and stationary. Under given thermal conditions, a stationary one-dimensional temperature field for the layer k=1.2...n is described by the differential equation of thermal conductivity. The accuracy of solving the problems is related to the approximation of the temperature distribution in the layers by expression. When the layer thickness decreases, the accuracy increases, and the continuous functions change in steps. In order to achieve the required accuracy, each of the two layers of the road surface (fiber concrete, ShchMA-15 asphalt concrete) is distributed into several sublayers with constant thermal characteristics. Stationary temperatures at the boundaries of the sublayers at a given heat flux are obtained. The dependence of the heating system temperatures on the heat flow supplied to the electrically conductive grid and the possibility of providing a positive temperature on the coating surface at a negative ambient temperature are determined. The heat-insulating properties of the thermal insulation layer ("Pinosital" bulk foam glass) have been tested and the efficiency of its use in construction has been confirmed.

Key words: *fibroelectric concrete, road cover, crushed stone and mastic asphalt concrete, thermal conductivity, boundary conditions, thermophysical characteristics eating system, heat flow, differential equation of thermal conductivity.*

Formulation of the problem. Winter maintenance of roads is the most difficult type of maintenance. Under the influence of winter weather and climatic factors, transport and operational characteristics and traffic conditions of highways change the speed of vehicles is reduced by 2–2.5 times, their productivity by 30–40%, and the cost of transportation increases by 25–30% [1]. At the same time, winter slipperiness is the cause of up to 82% of traffic accidents and accidents [2]. Thus, losses and general expenses from the influence of weather and climatic conditions on the functioning of the road transport system make the task of safety of its provision the most urgent both in the countries of the nearest and far abroad.

Despite the different approaches to this issue in countries with different climatic conditions, there is a common strategy for safe winter road maintenance, which includes the search for new anti-icing materials together with promising research and practical work to develop effective and environmentally friendly technological solutions to remove the ice from the floor [3–4]. Such solutions include environmentally friendly construction of heated pavement [5–6] using a monolithic layer of fiber concrete [7–8], developed with the participation of the author. Taking into account the fact that the calculation methods for the heating coatings are not studied properly, there are no any norms and classifications on this issue, that is why the research in this direction can be considered relevant and promising.

Analysis of recent research publications. The design of the heating coating requires thermal calculation, which determines the possibility of achieving a thermal effect – to obtain on the surface of the coating enough temperature for melting snow and ice in external negative temperature conditions. To solve this problem it is necessary to apply the theory of thermal conductivity. The basics of the theory of thermal conductivity are given in the works of B. Boli and J. Weiner, A.A. Ilyushin and B.E. Pobedri, V.I. Belyaev and A.A. Radyno, B.G. Koreneva, I.A. Motovilovets, Ya.S. Pidstrigach, V.A. Lomakin and Y.M. Koliano, S.M. Konstantinov. Asymptotic methods for solving problems of the theory of thermal conductivity and thermoelasticity are considered by I.Y. Zino and E.A. Tropp. Engineering and analytical methods in thermal conductivity problems are covered in the works of V.S. Zarubina, E.M. Kartashova, G.N. Dulneva, A.V. Sigalova and V.G.Parfyonova. Research of temperature crack resistance and issues of increasing the durability of asphalt concrete layers of road surfaces dedicated to a number of works by O.V. Mozgovyi.

Research of physical and mechanical properties of a covering depending on temperature and deformation rates are covered in the works of I.P. Homelyak [9]. Main issues of thermoelasticity in homogeneous structures, considered by V.M. Maisel, in the future generalized for layered structures V.G. Piskunov and V.S. Sipetov [10].

For layered structures, which include heating coating, piecewise linear laws of temperature distribution are used, similar to the broken line hypothesis for a package of issues in stress problems . In this case, the properties of the layers are taken into account in general , as for the linear law of temperature distribution in a homogeneous body thickness, and the order of the system of thermal equations does not depend on the number of layers. Averaging thermophysical parameters over the thickness of the layers, E.I. Starovoitov [11] reduced the problem of thermal conductivity in a three-layer plate to determine the temperature field in a homogeneous plate with modified thermophysical characteristics.

V.G. Piskunov and V.S. Sipetov [12] to describe the temperature distribution over the thickness of layered systems proposed a nonlinear law, which allows to refuse introduction of such meanings, as average temperature and it`s difference on thickness of a package of layers. In addition, it is possible to describe the nonlinear character of the temperature distribution over the thickness, replacing it with piecewise-linear, in this case, to achieve sufficient accuracy, each layer can be divided into sublayers, which is effective for solving the problem of thermal state of layered structures.

For the calculation of layered orthotropic thermosensitive shells and plates under force and heat O.M. Demchuk used an iterative approach [13]. The system of differential equations and boundary conditions of the stationary problem of thermal conductivity is obtained by variation, which was further used to develop a method of thermal calculation of heated road surfaces.

Formulation article goals. The purpose of research is to develop a method of thermal calculation of heated pavement with a layer of conductive concrete for the safety of its maintenance in the winter.

Presenting main material. The calculation is used to solve the thermal problem for the heating system that forms the coating, scilicet the problem of thermal conductivity under certain thermal boundary conditions and contact conditions of the layers [13].

The heating system is a layered body of total thickness „h", collected from „n" isotropic layers and assigned to the coordinates *0X, 0Z* (Fig. 1). The order of the layers in the system is arbitrary.

Physico-mechanical and thermophysical characteristics of layers $k = 1, 2, ...n$ are connecting with direction *0Z* (within the layer are constant). On the outer (upper) surface ($Z = h$) evenly distributed stationary temperature field *T(h)=T.*

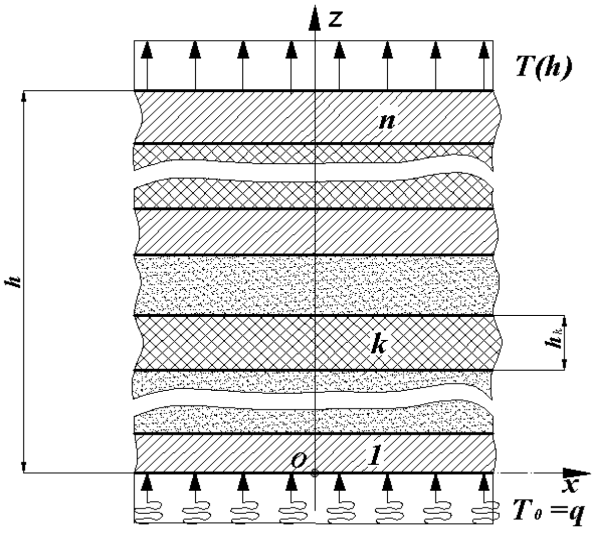

Fig. 1. Fragment of a layered body in the temperature field

Through the lower surface ($Z = 0$)a heat flow of a given power is working $T(0) = q$. Heat transfer goes from the lower surface to the upper – perpendicular to the package of layers (along the axis *0Z)*. So, the heat transfer problem is one-dimensional and stationary. Under given thermal conditions, a stationary one-dimensional temperature field for the layer $k = 1,2,...n$ is described by the following differential equation thermal conductivity:

$$\lambda_z^{(k)} \frac{d^2 T^{(k)}(z)}{dz^2} = 0, \tag{1}$$

Where $\lambda_z^{(k)}$ – the thermal conductivity of the layer *k*;

$T^{(k)}(z)$ – the law of temperature distribution in the layer *k*.

The thermal conductivity problem described by equation (1) meets the following basic boundary conditions:

– temperature on the outer surface ($Z = h$) body (boundary condition of the first kind)

$$T^{(n)}_{,}(h) = T; \tag{2}$$

– given the intensity of heat flow through the lower ($Z = 0$) surface of the body (boundary condition of the second kind)

$$\lambda_z^{(1)} \frac{d\,T^{(1)}(z)}{dz} = q; \tag{3}$$

– A partial case of boundary conditions of the second kind is the condition of thermal insulation of the body surface ($q = 0$);

– given the law of convective heat transfer between the body surface and the environment (boundary condition of the third kind)

$$\lambda_z^{(n)} \frac{d\,T^{(n)}(z)}{dz} = \alpha\left(\mathrm{T} - \mathrm{T}_\infty\right), \tag{4}$$

Where α – heat transfer coefficient, which depends on the thermal and physical characteristics of the body surface and the environment;

$T_\circ$ – surrounding environment temperature.

At the boundaries of the layers the conditions of "ideal" thermal contact are fulfilled, which for the common surfaces of the layers *(k)* , *(k-1)* presented as:

$$T^{(k)} = T^{(k-1)};\ \lambda_z^{(k)} \frac{dT^{(k)}(z)}{dz} = \lambda_z^{(k-1)} \frac{dT^{(k-1)}(z)}{dz}\ . \tag{5}$$

Conditions (5) determine the continuity of temperature and heat flux at the boundaries of the layers.

To solve the thermal problem, the hypothesis of temperature distribution in layers was used $k = 1,2,...n$ on the thickness of the system (3):

$$\mathrm{T}^{(\mathrm{k})}(\mathrm{z}) = \sum_{m=0}^{1} d_{1m}^{(k)}\, t_m + d_{2m}^{(k)} q_m = d_{10}^{(k)} t_0 + d_{20}^{(k)} q_0 + d_{11}^{(k)} t_1 + d_{21}^{(k)} q_1, \tag{6}$$

where t_m and q_m – looking functions of the reduction surface ($Z = 0$),which describe the temperature and heat flux (*m*=0), also the rate of change of these parameters over time (*m*=1);

$$d_{20}^{(k)}(z) = \int_0^z \left(\lambda_z^{(k)}\right)^{-1} dz;\ \ d_{11}^{(k)}(z) = \int_0^z \left(\lambda_z^{(k)}\right)^{-1} \int_0^z c_z^{(k)} d_{10}\, dz\ dz;$$

$$d_{21}^{(k)}(z) = \int_0^z \left(\lambda_z^{(k)}\right)^{-1} \int_0^z c_z^{(k)} d_{20}\, dz\ dz$$

$d_{10}^{(k)}(z) = 1$ – given normal functions;

$c_z^{(k)}$ – specific heat of the layers.

In the temperature distribution (6) not only thermal conductivity coefficients are taken into account $\lambda_z^{(k)}$, also a specific heat $c_z^{(k)}$ the material of the coating layers. The largest order of the polynomial that approximates the temperature within each layer for this model is 3. The general order of the system to which equation (1) reduces is 8.

According to the described method, the thermal problem for the heating coating is solved. To the lower ($Z = 0$) surface of the layer of fiber concrete with a thermal conductivity $\lambda_z^{(1)} = 0{,}84$ VT/m°C and specific heat $c_z^{(1)} = 0{,}47$ kDg/kg °C the heat stream from a carbon grid of the set power moves q. On the surface of the coating ($Z = 0{,}11$ м) with thermal conductivity $\lambda_z^{(n)} = 1{,}68$ VT/m °C and heat capacity $c_z^{(n)} = 1{,}05$ kDg/kg°C you should to get the needed temperature to melt the snow and prevent ice +(2 – 10) °C at ambient temperature –20 °C.

The accuracy of solving the problems is related to the approximation of the temperature distribution in the layers by expression (6). When the layer thickness decreases, the accuracy increases, and the continuous functions change in steps. In order to achieve the required accuracy, each of the two layers of the road surface (fiber concrete [6], ShchMA-15 asphalt concrete [14]) is distributed into several sublayers with constant thermal characteristics.

– So, in general, we get a multilayer system for road surface:

– a layer of fibrobetel thick $h = 0{,}05$ m divided into 10 sublayers $h = 0{,}005$ m;

– a layer of ShchMA thick $h = 0{,}06$ m on 10 sublayers on $h = 0{,}006$ m.

– An example of the obtained stationary temperatures at the boundaries of the sublayers at heat flow $q = 900$ Wt and external environment temperature –20 °C for pavement are shown in table 1.

The next calculations are making with a further increase in heat flux from

q=900 Wt·to *q=1400 Wt*·(with a step ∆q*Wt*).

The solution of equation (1) allowed to determine the dependence of the temperatures of the heating system on the heat flux, which is fed to the electrically conductive grid. So, table 2 shows the results of the calculation for the road heating surface.

The calculations establish the possibility of providing at an ambient temperature of –20° C on the surface of the road surface a positive temperature from +2.2 ° C to + 11 ° C at a heat flux from 1000 W to 1400 W.

So, if the temperature along the thickness of the layer of fibrobetal for the pavement is maintained from + (78.2–121.2)° C to + (30.6–54.6)° C, the surface of the pavement provides the necessary thermal effect.

The heat-insulating properties and a layer of thermal insulation are checked. According to Fourier's law, the amount of heat (q, Wt), which is transferred to a layer of thermal insulation thickness Δl= 05m per plane of a standard cement concrete slab (s) depends on the thermal conductivity of the thermal insulation material (λ), temperature gradient on the surfaces of the layer for some time (∅T) for time (t).

$$q = \lambda \frac{\Delta T}{\Delta l} st. \qquad (7)$$

If we assume that the thermal insulation layer is supplied with heat of 1400 W, then from formula (7) the temperature gradient °C.

$$\Delta T = \frac{q\Delta l}{\lambda st} = \frac{1400 \cdot 0{,}05}{0{,}059 \cdot 18 \cdot 1} = 66$$

When the value of the temperature on the upper surface of the thermal insulation layer Tv = 121°C, the temperature on its lower surface will be

$$T_н = T_в - \Delta T = 121 - 66 = 55\,°C,$$

which confirms the effectiveness of the adopted thermal insulation material.

Conclusions. The thermal calculation of the heated road surface according to the above method confirmed the effect of heating the road surface to a positive temperature at a negative ambient temperature. The further research in this area can be considered relevant and promising.

Table 1

The results of the calculation of the temperature field in the heater system (*q*=900 *Wt*)

Fibrobetel layer, h = 0,05 м ($\lambda_z^{(1)}$ = 0,84 Wt/m°C; $c_z^{(1)}$ = 0,47 kDg/kg°C)											
h_k, м	0,000	0,005	0,010	0,015	0,020	0,025	0,030	0,035	0,040	0,045	0,050
T, °C	67,38	64,10	59,81	55,53	51,26	46,96	42,67	38,38	34,10	29,81	24,60
Surface SHMA, h = 0,06 м ($\lambda_z^{(n)}$ = 1,68 Wt/m °C; $c_z^{(n)}$ = 1,05 kDg/kg°C)											
h_k, м	0,050	0,056	0,062	0,068	0,074	0,080	0,086	0,092	0,098	0,104	0,110
T, °C	24,60	22,97	20,42	17,87	15,31	12,76	10,21	7,65	5,10	2,55	+0,00

Table 2

Dependence of pavement temperatures on heat flow

Heat flow, Wt	The temperature of the lower surface of the fibrobetel, °C	∅t, °C	Fibrobetel boundary surface temperature, °C	∅t, °C	Coating surface temperature, °C	∅t, °C
900	+67,4	10,8	+24,6	6	0,00	2,2
1000	+78,2	10,8	+30,6	6	+2,2	2,2
1100	+89,0	10,8	+36,6	6	+4,4	2,2
1200	+99,7	10,8	+42,6	6	+6,6	2,2
1300	+110,4	10,8	+48,6	6	+8,8	2,2
1400	+121,2	10,8	+54,6	6	+11,0	2,2

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Володько О.В., Рогова Н.В. МЕТОДИКА ТЕПЛОВОГО РОЗРАХУНКУ НАГРІВНОГО ДОРОЖНЬОГО ПОКРИТТЯ

Безпечне утримання автомобільних доріг, особливо в зимовий період експлуатації, є актуальним питанням сьогодення. Серед різноманітних традиційних способів боротьби зі снігом та ожеледицею на покритті існує і альтернативний спосіб, зокрема використання нагрівних конструкцій покриттів. Розроблено методику теплового розрахунку екологічно безпечного нагрівного дорожнього покриття, а саме вирішено задачу теплопровідності при заданих певних теплових граничних умовах та умовах контакту шарів. Нагрівна система покриття складається із щебенево-мастикового асфальтобетону, шару електропровідного бетону (фібробетону), вуглецевої сітки для подачі струму та прошарку термоізоляції. Для розв’язання теплової задачі використана гіпотеза розподілу температури в прошарках нагрівного покриття по товщині системи. Задані фізико-механічні та теплофізичні характеристики шарів та граничні умови на їхні поверхні. Крізь нижню поверхню діє тепловий потік заданої потужності. Перенос тепла відбувається від нижньої поверхні до верхньої – перпендикулярно пакету шарів, що робить задачу теплопереносу одновимірною та стаціонарною. За заданих теплових умов стаціонарне одновимірне температурне поле для шару k=1.2...n описується диференційним рівнянням теплопровідності. Точність розв’язання задачі пов’язана з апроксимацією розподілу температури в шарах. Зі зменшенням товщини шарів точність зростає, а неперервні функції змінюються на ступеневі. З метою досягнення необхідної точності кожен із двох шарів дорожнього покриття (фібробетон, щебенево-мастиковий асфальтобетон) розподіляється на декілька підшарів із постійними тепловими характеристиками. Отримано стаціонарні температури на границях підшарів за заданого теплового потоку. Визначено залежність температур нагрівної системи від теплового потоку, який подається на електропровідну сітку, та можливість забезпечення додатної температури на поверхні покриття за від’ємної температурі зовнішнього середовища. Перевірені теплоізоляційні властивості шару термоізоляції (насипного піноскла «Піноситал») та підтверджено ефективність його використання в конструкції.

Ключові слова: *фіброелектробетон, дорожнє покриття, щебенево-мастиковий асфальтобетон, теплопровідність, граничні умови, теплофізичні характеристики, нагрівна система, тепловий потік, диференційне рівняння теплопровідності.*