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CALCULATION OF TEMPERATURE MODES IN PROVIDING FLEXIBLE ROAD PAVEMENT PATCHING

Statement of the problem. The quality of flexible road pavement repair depends on the temperature of compaction of road concrete mix. The change in temperature of the mixture depends on external factors (ambient temperature, humidity, presence of wind), as well as of the technology of works. The purpose of the paper is to develop a thermal physical model of processed mix depending on the type of the mix, external natural factors and technology of hot mix laying and compaction.

Results. The method of finite elements is used for constructing the thermal physical model of asphalt concrete mix. Analytical description of the process of heat transfer is provided with the use of heat conduction and convection models. Boundary conditions are the initial distribution of the temperature of the treated surfaces after preliminary works before and after mixture filling. Adaptation of the model is performed at the expense of changes in the coefficients of thermal conductivity depending on the current distribution of the surface temperature of the treated mix.

Conclusions. Thermal physical model allows to define the duration of the technology of repair with consideration for the temperature modes of hot mixture.

Keywords: asphalt-concrete mix, thermal conductivity, convection; road pavement repair, finite element method.

Introduction

The major factor to affect the quality of hot-mix asphalt concrete surfacing is the temperature. The development of the model of change in the temperature of asphalt pavement (mix) in low amounts during the repairs allows one to come up with guidelines on how to establish technological schemes for laying hot-mix asphalt surfacing in order to improve the effectiveness and thus durability of the works carried out [1 3].

The object of the research was a special technologically developed rectangular strip cut in a non-rigid road surface with the size of $l \;\; s \le 1 \;\; 0.5$ m^2 and the depth of $h \le 0.15$ m covered with a hot-asphalt concrete mix ($t \le 250$ ^{0}C) with the uneven distribution of the temperature with it being up to 1/3h up the road surface.

The initial conditions and adaptation of the parameters of the model are adhered to using an infrared scanner with a 320 240 pixel matrix and USB-slot to connect with a portable computer.

The model brings the following two kinds of heat transfer (heat conductivity and convection) in accordance [4]. The process of modeling takes the following stages: 1) designing an analytical model; 2) developing an imitation model; 3) a natural experiment model to connect the heat physical parameters of the imitation model.

1. Designing an analytical heat transfer model. The analytical model is based on the heat conductivity equation for an isotropic heterogeneous medium:

$$\frac{\partial}{\partial t}\left(pc_V T\right)=\frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right)+F, \qquad (1)$$

where ρ is the density of a medium; c_V is the heat capacity of a medium in the same volume; t is the time; x, y, z are the coordinates; $T = T(x, y, z, t)$ is the temperature which is calculated using a heat transfer equation; λ is the heat transfer coefficient; $F = F(x, y, z, t)$ is the specified density of heat sources.

The analytical heat transfer model was based on a heat flow model which is determined by the Fourier equation:

$$q=-\lambda\frac{dT}{dx}, \qquad (2)$$

where q is the surface density of the heat flow that goes through the plane which is perpendicular to the heat flow, Watt/m^2; λ is the heat transfer of the material, Watt/(m degrees); T is the temperature that varies along the axis x, degrees (C); dT/dx is the temperature gradient, degrees/m.

In order to account for a change in heat transfer caused by the temperature of the mix, the empirical formula by O. Ye. Vlasov was used:

$$\lambda_0 = \lambda_T / (1+\beta T), \tag{3}$$

where λ_0 is the heat conductivity of the material at 0 C; λ_T is the heat conductivity of the material at T C; β is the temperature coefficient of change in heat conductivity (for different materials it is about 0.0025 (degrees)$^{-1}$); T is the temperature of the material when its heat conductivity coefficient is λ_T.

The convective heat transfer is based on the Newton-Richman law that a heat flow Q from the wall to the air is proportionate to the heat transfer surface and difference between the temperatures of the solid wall T_c and the air temperature T_B.

The empirical formula was used which is based on the fact cooling of hot-mix asphalt concrete in a thin layer regardless of its composition, air temperature and wind velocity complies with the exponential law [1]:

$$Ln\left(\frac{T_0-T_B}{T_P-T_B}\right) = m\cdot\tau = \frac{2\cdot\lambda}{\gamma\cdot c\cdot h}t, \tag{4}$$

where t is the time, h; T_0 is the temperature of the mix at the initial moment of time, degrees; T_p is the temperature of the mix at a design moment of time, degrees; m is the rate of cooling, (degrees)$^{-1}$; λ is the coefficient of the heat transfer of the mix, Watt/(m degree); c is the heat capacity of the mix, J/(kg degree); γ is the volumetric mass of the mix, kg/m^3; h is the thickness of a layer of the mix, m.

2. Designing the imitation model of heat transfer. The imitation model was designed by means of a network model that included 7 horizontal layers (Fig. 1) with each of the layers split into homogeneous rectangular parallelepiped (Fig. 2).

The heat transfer occurred between them through the side face in the vertical $\overline{OZ}$ and horizontal $\overline{OXY}$ planes according to the formulas (1) (4) using the Monte-Carlo method.

The upper layer ($Z = 6$) is the air one and is located over the road surface proper where the works are underway; the lower layer ($Z = 0$) is the soil; the other layers are laid asphalt mix. The homogeneity of the parallelepipeds suggests they have similar mass and thereby heat energy characteristics with little change (up to 25 %) in the height.

The model was designed using the *Excel* environment, which allowed a significant increase in the rate of the calculation as there was a switch to multiprocessor computing machines and also a better understanding of the heat transfer taking place in any of section [5]. The imitation model includes a stochastic model of the heat transfer coefficient, specification of the boundary conditions (the matrix of the temperature distribution in the underneath soil prior to laying the asphalt mix and the matrix of the horizontal temperature distribution along the surface of the asphalt concrete mix following it being laid), stochastic model of heat transfer. The modeling step is determined by how long the works take to carry out and is about 1 % of the time (1 min).

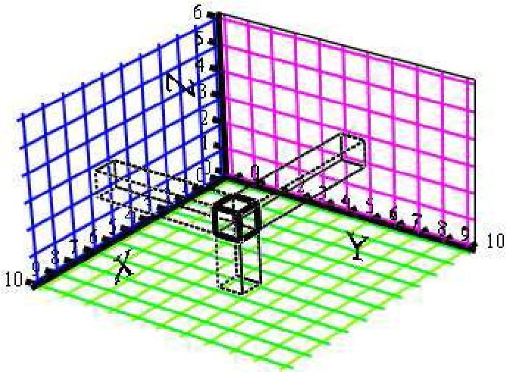


Fig. 1. Network model

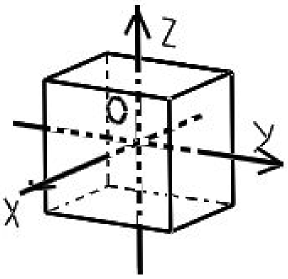


Fig. 2. Element
of the network model

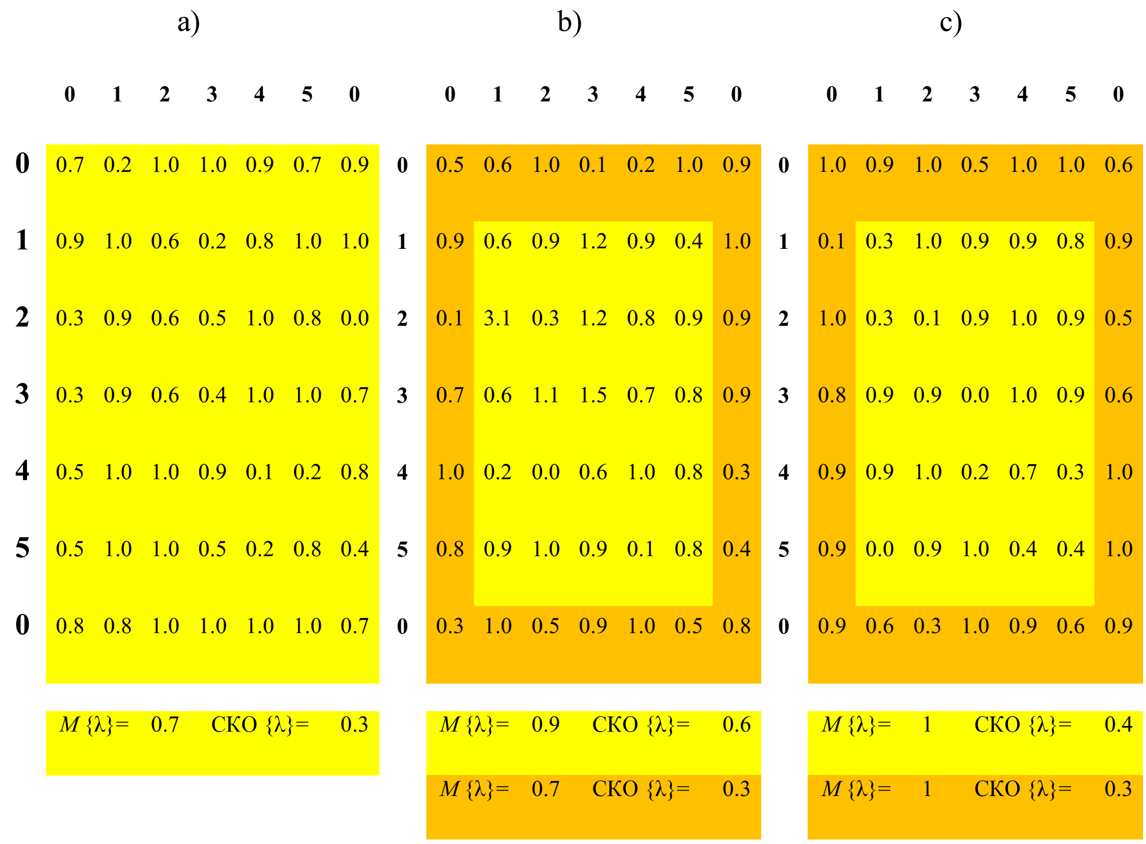
The stochastic modeling of the heat conductivity coefficients λ involved the imitation of modeling the heat conductivity coefficients in each step for each of the 6 faces of the rectangular parallelepiped (see Fig. 2) of the network model grouped into three matrices:

– matrix of the coefficients of conventional heat transfer of air masses (Fig. 3a) in the upper layer of the network model (3) where $\lambda_0 = 0.022$– 0.026 Watt/(m degree);

– matrix of the diffusion heat transfer (Fig. 3b) for all the middle faces of the network model (3) where $\lambda_0 = 0.70$– 0.75 Watt/(m degrees);

– matrix of the coefficients of diffusion heat transfer (Fig. 3c) for the lower layer of the network model (3) where $\lambda_0 = 0.70$– 0.8 Watt/(m degrees).

It should be noted that the element of the model for each layer of the laid mix (Fig. 3, 4, 7, 8) has the coordinates: {0, 1, 2, 3, 4, 5, 0} × {0, 1, 2, 3, 4, 5, 0} and if one of the coordinates is zero, this boundary layer of the old surfacing is related to the one being laid.



a)

	0	1	2	3	4	5	0
0	0.7	0.2	1.0	1.0	0.9	0.7	0.9
1	0.9	1.0	0.6	0.2	0.8	1.0	1.0
2	0.3	0.9	0.6	0.5	1.0	0.8	0.0
3	0.3	0.9	0.6	0.4	1.0	1.0	0.7
4	0.5	1.0	1.0	0.9	0.1	0.2	0.8
5	0.5	1.0	1.0	0.5	0.2	0.8	0.4
0	0.8	0.8	1.0	1.0	1.0	1.0	0.7

$M\{\lambda\}$= 0.7 СКО {λ}= 0.3

b)

	0	1	2	3	4	5	0
0	0.5	0.6	1.0	0.1	0.2	1.0	0.9
1	0.9	0.6	0.9	1.2	0.9	0.4	1.0
2	0.1	3.1	0.3	1.2	0.8	0.9	0.9
3	0.7	0.6	1.1	1.5	0.7	0.8	0.9
4	1.0	0.2	0.0	0.6	1.0	0.8	0.3
5	0.8	0.9	1.0	0.9	0.1	0.8	0.4
0	0.3	1.0	0.5	0.9	1.0	0.5	0.8

$M\{\lambda\}$= 0.9 СКО {λ}= 0.6

$M\{\lambda\}$= 0.7 СКО {λ}= 0.3

c)

	0	1	2	3	4	5	0
0	1.0	0.9	1.0	0.5	1.0	1.0	0.6
1	0.1	0.3	1.0	0.9	0.9	0.8	0.9
2	1.0	0.3	0.1	0.9	1.0	0.9	0.5
3	0.8	0.9	0.9	0.0	1.0	0.9	0.6
4	0.9	0.9	1.0	0.2	0.7	0.3	1.0
5	0.9	0.0	0.9	1.0	0.4	0.4	1.0
0	0.9	0.6	0.3	1.0	0.9	0.6	0.9

$M\{\lambda\}$= 1 СКО {λ}= 0.4

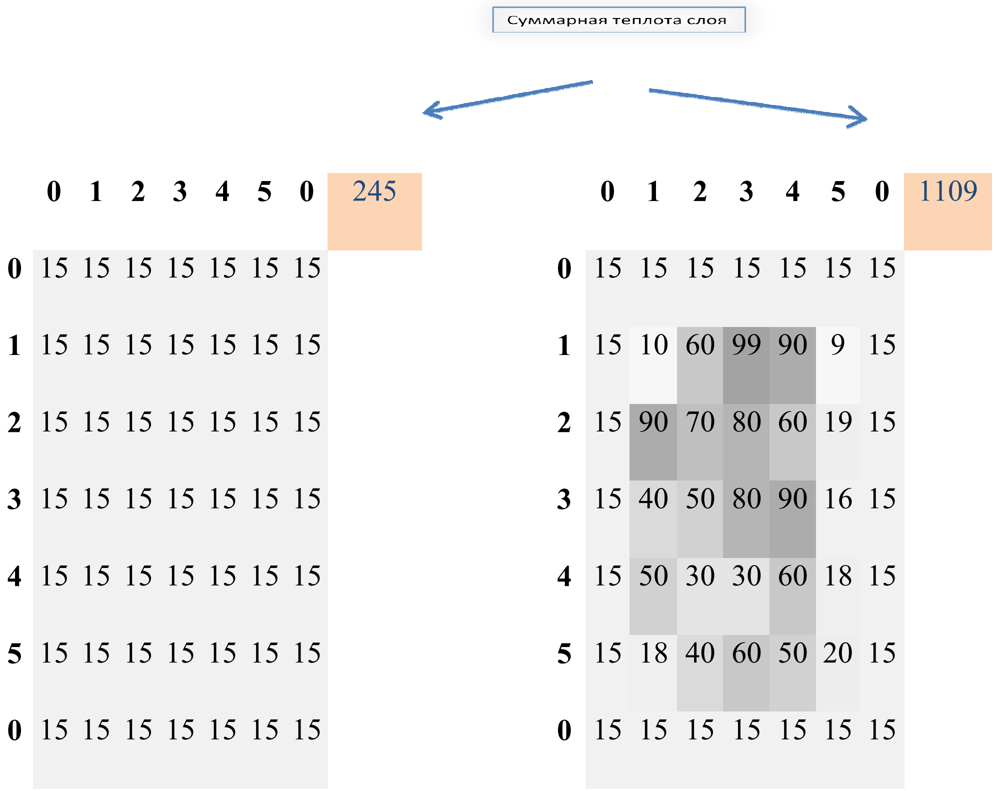
$M\{\lambda\}$= 1 СКО {λ}= 0.3

Fig. 3. Modeling the heat conductivity coefficient:
a) convectional heat transfer of the upper layer; b) diffusion heat transfer of the inside layers;
c) diffusion heat transfer of the underneath soil

As a result of modeling, a mathematical expectation $M\{\lambda\}$ and range dispersion СКО $\{\lambda\}$ of the parameter λ for all the layers of the network model as well as the coefficients λ located along the parameter of each layer were evaluated for the assessment of the viability of modeling the parameter λ.

The initial specification of the temperature distribution of the underneath layer and surface of the laid mix was obtained by making the image of the infrared scanner digital (Fig. 4).

The index of the total heat of the layer was determined as the sum of the temperatures of all of 49 elements of the layer (in Fig. 3, 4, 7, 8 the temperature field is connected to the single temperature gradation scale as shown in Fig. 5).



	0	1	2	3	4	5	0	245
0	15	15	15	15	15	15	15	
1	15	15	15	15	15	15	15	
2	15	15	15	15	15	15	15	
3	15	15	15	15	15	15	15	
4	15	15	15	15	15	15	15	
5	15	15	15	15	15	15	15	
0	15	15	15	15	15	15	15	

a) the temperature of the underneath soil, C

	0	1	2	3	4	5	0	1109
0	15	15	15	15	15	15	15	
1	15	10	60	99	90	9	15	
2	15	90	70	80	60	19	15	
3	15	40	50	80	90	16	15	
4	15	50	30	30	60	18	15	
5	15	18	40	60	50	20	15	
0	15	15	15	15	15	15	15	

b) the temperature of the upper layer of the laid mix, C

Fig. 4. Boundary conditions of the model:

Суммарная теплота слоя = Total heat of the layer

Fig. 5.Temperature gradation scale, C

The stochastic model of heat transfer is based on the fact that each finite element of the model shaped like a rectangular parallelepiped (see Fig. 2) is split into 6 sub elements with each of them having a corresponding face of the rectangular parallelepiped as its base and the same vortex, i.e. the centre of this parallelepiped (Fig. 6). The heat transfer model is based on the formula (4).

Two matrices are calculated for each layer i of asphalt concrete mix: the matrix T_{ij} is the distribution of the temperature of the layer i in the iteration step j and the matrix $T_{i\,j+1}$ is the distribution of the temperature of the layer i in the iteration step $j+1$. Equally calculated procedures that include six sum operations provide the temperature distribution of each network element of the model (Fig. 6) based on the comparison of the temperatures of its six sub elements with their corresponding neighboring sub elements. Using the formula (4) and data as shown in Fig. 4, obtaining the matrix $T_{i\,j+1}$ based on the matrix T_{ij} is not a difficult task to perform.

Fig. 7 and 8 show the results of the temperature distribution for the first and $j = 10$ steps of modeling of the 1st, 3rd and the last layer of the asphalt concrete layer correspondingly.

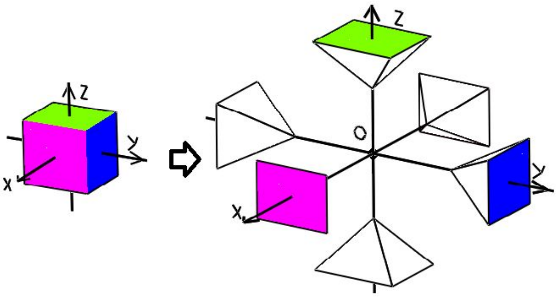
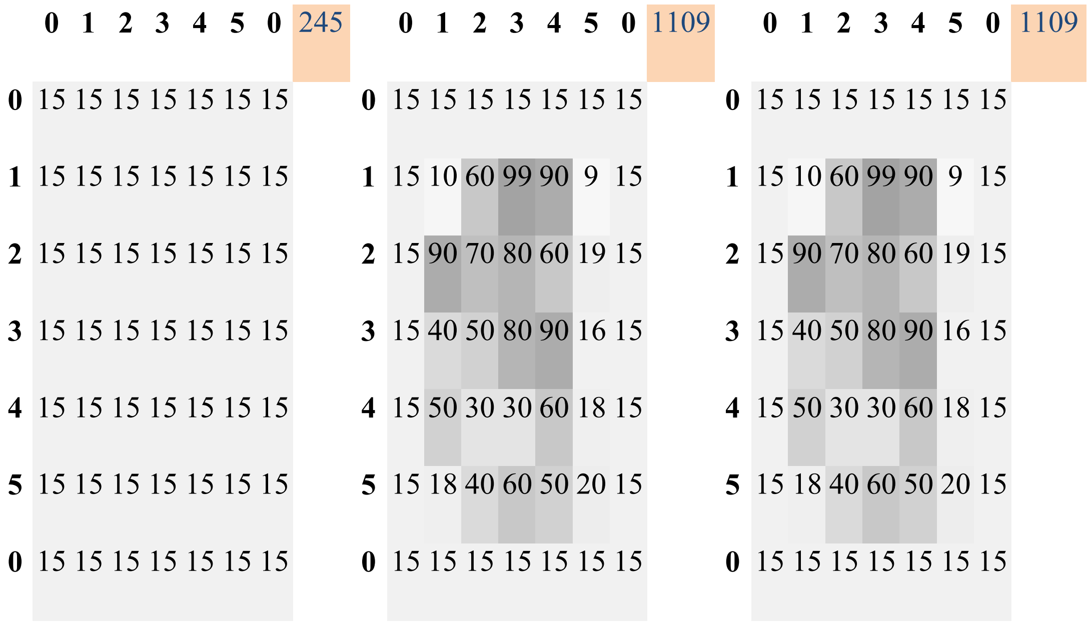


Fig. 6. Structure of the heat transfer model



a)

	0	**1**	**2**	**3**	**4**	**5**	**0**	245
0	15	15	15	15	15	15	15	
1	15	15	15	15	15	15	15	
2	15	15	15	15	15	15	15	
3	15	15	15	15	15	15	15	
4	15	15	15	15	15	15	15	
5	15	15	15	15	15	15	15	
0	15	15	15	15	15	15	15	

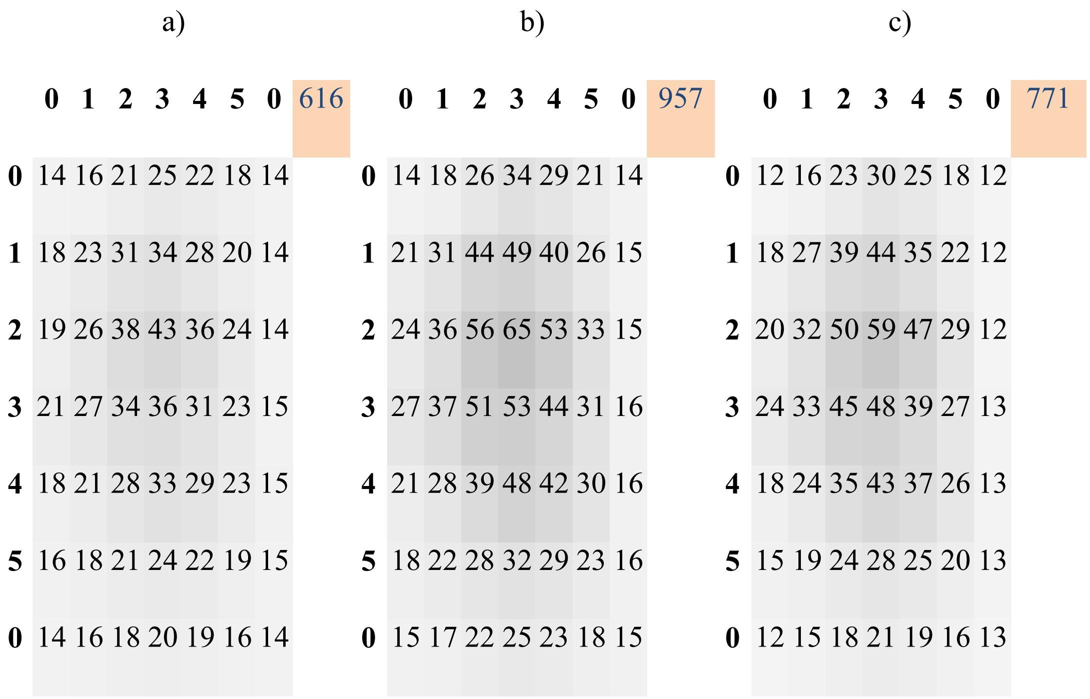
b)

	0	**1**	**2**	**3**	**4**	**5**	**0**	1109
0	15	15	15	15	15	15	15	
1	15	10	60	99	90	9	15	
2	15	90	70	80	60	19	15	
3	15	40	50	80	90	16	15	
4	15	50	30	30	60	18	15	
5	15	18	40	60	50	20	15	
0	15	15	15	15	15	15	15	

c)

	0	**1**	**2**	**3**	**4**	**5**	**0**	1109
0	15	15	15	15	15	15	15	
1	15	10	60	99	90	9	15	
2	15	90	70	80	60	19	15	
3	15	40	50	80	90	16	15	
4	15	50	30	30	60	18	15	
5	15	18	40	60	50	20	15	
0	15	15	15	15	15	15	15	

Fig. 7. Initial interlayer temperature distribution, C:
a) the temperature of the underneath soil; b) the temperature of the middle layer;
c) the temperature of the upper layer



a)

	0	1	2	3	4	5	0	616
0	14	16	21	25	22	18	14	
1	18	23	31	34	28	20	14	
2	19	26	38	43	36	24	14	
3	21	27	34	36	31	23	15	
4	18	21	28	33	29	23	15	
5	16	18	21	24	22	19	15	
0	14	16	18	20	19	16	14	

b)

	0	1	2	3	4	5	0	957
0	14	18	26	34	29	21	14	
1	21	31	44	49	40	26	15	
2	24	36	56	65	53	33	15	
3	27	37	51	53	44	31	16	
4	21	28	39	48	42	30	16	
5	18	22	28	32	29	23	16	
0	15	17	22	25	23	18	15	

c)

	0	1	2	3	4	5	0	771
0	12	16	23	30	25	18	12	
1	18	27	39	44	35	22	12	
2	20	32	50	59	47	29	12	
3	24	33	45	48	39	27	13	
4	18	24	35	43	37	26	13	
5	15	19	24	28	25	20	13	
0	12	15	18	21	19	16	13	

Fig. 8. Temperature distribution following 10 modeling steps, C:
a) the temperature of the underneath soil; b) the temperature of the middle layer;
c) the temperature of the upper layer

3. Natural experiment model

In the natural experiment model there will be the assessment of the viability of the designed model and data obtained using the infrared scanner. The following distribution of the decreasing heat energy was obtained (Fig. 9).

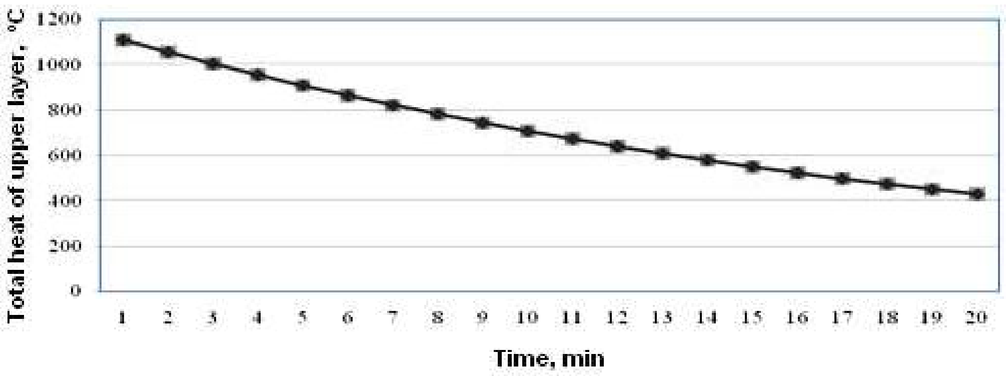


Fig. 9. Graph of the heat losses depending on the time

Conclusions

1. A multi-layer heat physical model that allows one to determine how long the technology of carrying out repair works with respect to the temperature mode of the laid hot-mix asphalt will endure.

2. The authors found out that the major parameter of the model is the heat transfer coefficient that is dependent on the compression coefficient of a hot-mix asphalt and natural factors.

3. A temperature field of the near-bottom surface of a surfacing being repaired prior to laying the hot mix and temperature distribution of the upper layer following laying of the hot mix has first been suggested as boundary conditions of a heat physical model. In order to track down the heat transfer coefficient, the temperature distribution of the upper layer of the compressed mix was also used.

4. The above approach was found not to require any temperature gauges embedded into the compressed mix and the necessary temperature parameters as the initial conditions and more suitable heat transfer coefficients can be read using the infrared scanner.

5. The authors have been the first to come up with the way the model of a multi-layer heat physical model based on a multi-sheet *Excel* workbooks can be used that permits hands-on tracking of the temperature distribution of any layer as well as their sections as repair work gets underway.

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