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Simulation of Temperature Regime of Pavement Layers in Transition Periods of Road Climatic Zone IV

Vladimir Petrovich Nosov, Michail Vasilievich Nemchinov, Nikita Vladimirovich Borisyuk, Vyacheslav Vasilievich Silkin, Ivan Alexandrovich Belyanin

Abstract: ***Pavement icing during short-term night temperature drops leads to deterioration of highway performances and increase in road traffic accidents (RTA) in Krasnodar Krai. Peculiar features of temperature regime in road climatic zone (RCZ) IV are analyzed. The considered climatic zone is characterized by frequent zero crossing temperatures of air and road pavement, sharp short-term temperature drops in nighttime, frequent icing of road pavement. Main factors are highlighted which effect temperature regime of road structures. Mathematical model is presented for prediction of road pavement temperature based on weather forecasts. Possibility to decrease the volume of pavement icing by means of thermophysical properties of pavement layers is analyzed.***

Keywords: ***highway, road pavement icing, temperature regime of road structures, thermophysical properties of building materials, winter maintenance.***

I. INTRODUCTION

Extended transition period in RCZ IV stipulates increased hazard of road pavement icing. The icing deteriorates adhesion and leads to increase in road accidents. According to statistical data of State Traffic Safety Inspectorate, Krasnodar krai occupies one of three top positions of Russian incidental regions [1]. One of the most important parameters effecting the formation of winter slipperiness is the temperature regime of road surface. Variation of temperature of pavement surface depends on thermophysical properties of pavement layers and weather conditions in their locations.

Therefore, the structures will response differently on variations of ambient temperature and intensity of solar radiation.

Hence, it is possible to assume possibility of buildup of thermal energy in day times and accumulation of stored heat during short-term night drops of temperatures in order to decrease hazard of pavement icing.

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* Correspondence Author

Vladimir Petrovich Nosov, MADI, 64, Leningradsky Prosp., Moscow, 125319, Russia.

Michail Vasilievich Nemchinov, MADI, 64, Leningradsky Prosp., Moscow, 125319, Russia.

Nikita Vladimirovich Borisyuk, MADI, 64, Leningradsky Prosp., Moscow, 125319, Russia.

Vyacheslav Vasilievich Silkin, MADI, 64, Leningradsky Prosp., Moscow, 125319, Russia.

Ivan Alexandrovich Belyanin, MADI, 64, Leningradsky Prosp., Moscow, 125319, Russia.

II. METHODS

A. Block diagram

Krasnodar krai is located in RCZ IV. The climate here is mostly moderate continental. Sharp weather vitiations are typical all the year round: monthly and daily variations of temperature are significant. Average many-year winter duration is 66 days. Average monthly temperatures in winter vary from +6.5°C to –13.0°C°.

Analysis of climatic data demonstrates that Krasnodar krai is characterized by frequent zero crossing temperatures. Such days are observed from November to March. The number of such days in months varies from 8 to 15 days per month. According to statistical data of State Traffic Safety Inspectorate, the highest number of RTA is in the months with the most frequent zero crossing temperatures of air and road pavement [1].

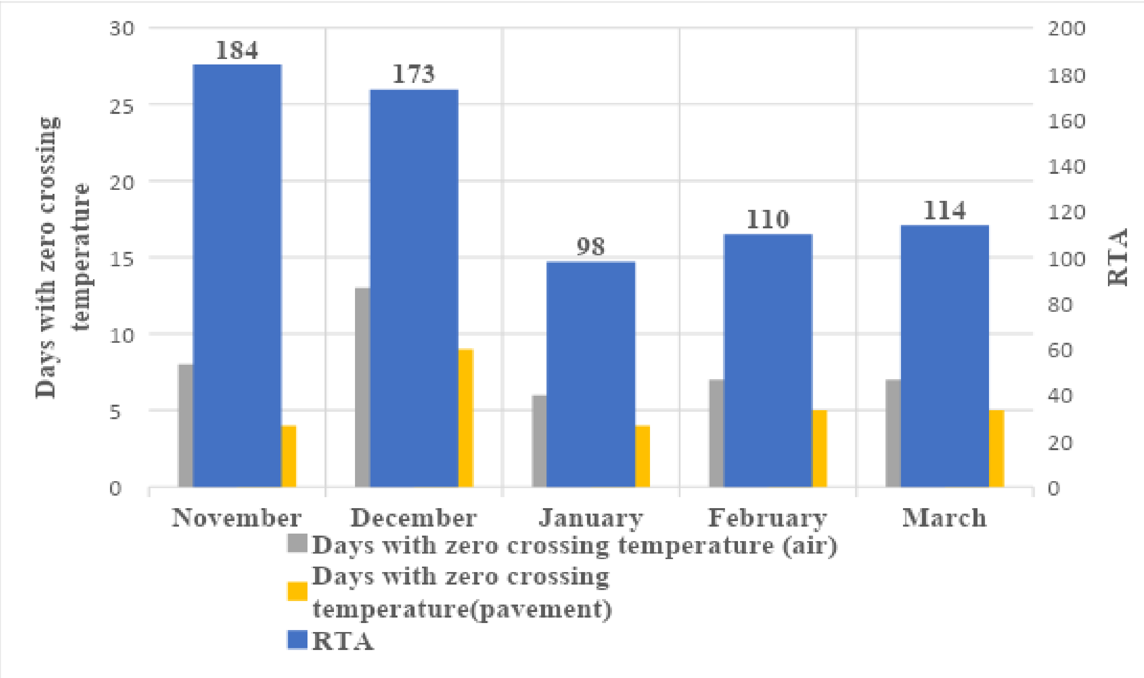

Fig. 1. RTA as a function of zero crossing temperature of air and pavement

Another peculiar feature of the region is the existence of numerous days with sharp short-term (2–3 hours) drops of air temperature at nights (Fig. 2). Characteristic case of double short-time zero crossing temperature attracts special attention.

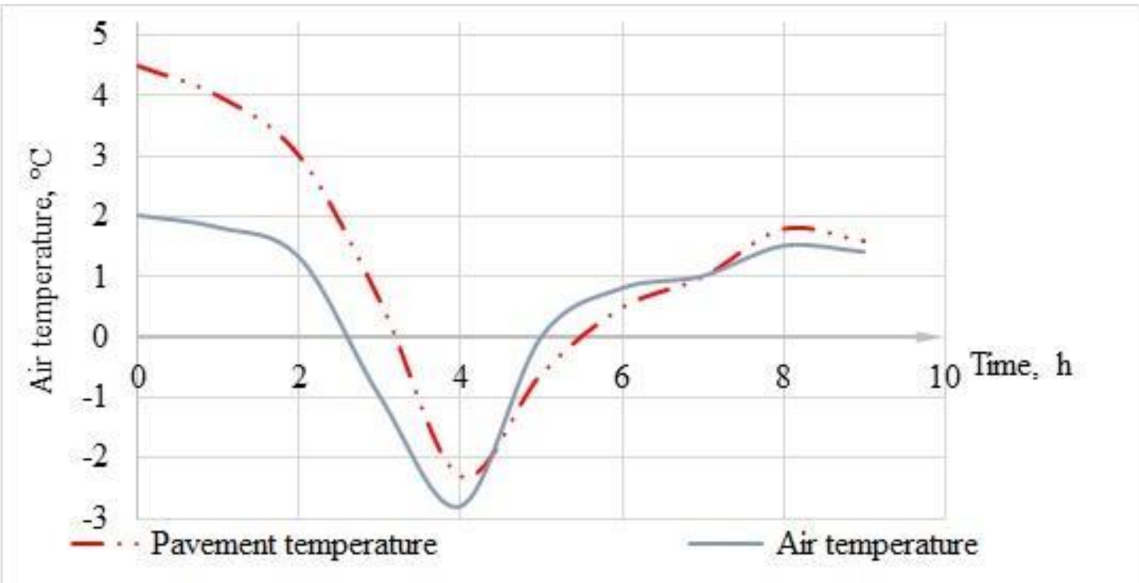

Fig. 2. Daily temperature variations of air and pavement

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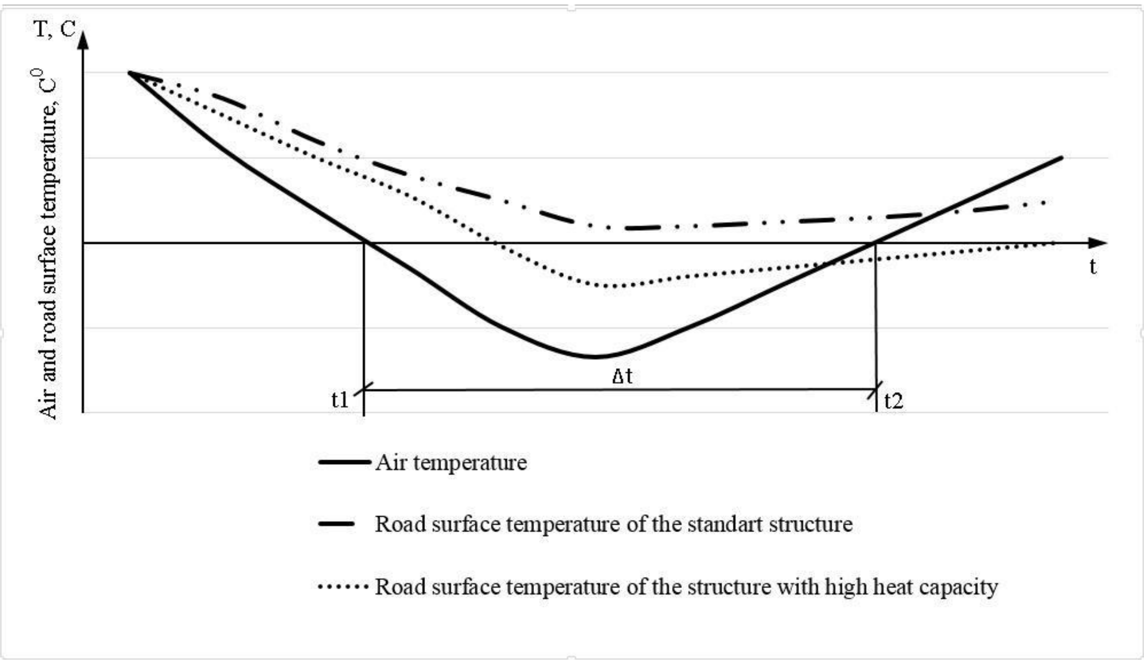

Fig. 3. Schematic view of double zero crossing temperature

As follows from Fig. 3, due to variation of heat capacity of road surface dressing, it is possible to achieve the fact that the amount of accumulated thermal energy in the structure would allow to prevent negative temperature on surface.

B. Algorithm

According to previous studies, the temperature regime of road pavement can be adjusted by arrangement of pavement layers with increased heat capacity.

Yinfei Du [2] analyzes possibility to decrease pavement temperature and heat radiation from pavement surface. Several variants of road surface dressing are considered. Three types of three-layer asphalt concrete coatings with various thermal conductance were compared:

Structure 1 with thermal conductance of the layers: λ_1 =1.8; λ_2=1.8; λ_3= 1.2 W/m*°C (POCS);

Structure 2 with thermal conductance of the layers: λ_1=1.4; λ_2=1.6; λ_3=1.8 W/m*°C (HCPS);

Structure 3 with thermal conductance of the layers: λ_1=1.2; λ_2=1.2; λ_3=1.2 W/m*°C (CS).

Comparison of the variants demonstrated that the surface temperature of Structure 1 upon heating was by 4.4°C lower than that of Structure 2 and by 1.5°C lower than that of Structure 3. It has been concluded that application of structures with higher thermal conductance of top layers leads to decrease in surface temperature by several degrees in comparison with other structures. Similar results were obtained in [3]. Yinfei Du [2] also states that thermal conductance of asphalt concrete layers can be adjusted by various additives, such as powdered graphite. Consequently, it is possible to obtain asphalt concrete layers with thermal conductance λ of 0.58–2.88 W/m*°C in comparison with the layers considered in this work: λ=0.40-1.4 W/m*°C.

Thermal properties of asphalt concrete structures with various porosity were compared in [4]. It was demonstrated that variation of porosity effected significantly the thermal properties of asphalt concrete. Thus, increase in porosity resulted in decrease in thermal conductance and specific heat capacity by 40%.

Possibility to reduce icing hazardous period for highways by estimation and selection of optimum engineering thermophysical parameters of road dressing structures was mentioned by Prof. Mikhailov [5] who stated that on the basis of daily heating–nightly cooling cycle, the icing hazardous period could be reduced by provision of optimum engineering properties of road structure.

In order to study the temperature regime of road structures in RCZ IV and possibility to decrease zero crossing temperatures, let us apply the mathematical model by Prof. Samodurova [6]. The model is based on differential equation of thermal conductance [7] and describes formation of various types of winter slipperiness. The basis of the model is prediction of road pavement temperature by meteorological data.

Road structure and road foundation are presented as multilayer system where each layer is characterized by certain thermophysical properties:

- thermal conductance (λ)
- specific heat capacity (c),
- density of structure layer (ρ)
- humidity (W_1).

Thermophysical properties of road construction materials and established temperature regime determine thermal inertia properties of road pavement, and its temperature will depend also on heat exchange between environment and road, which is characterized by cumulative coefficient of heat exchange.

Computational flowchart is as follows:

– Top layer of road pavement ⌊i, Ci, ρi, Wi, Hi;
– Bottom layer of road pavement ⌊i, Ci, ρi, Wi, Hi;
– Top layer of foundation ⌊i, Ci, ρi, Wi, Hi;
– Bottom layer of foundation ⌊i, Ci, ρi, Wi, Hi;

– Soil layer of road bed ⌊s, Cs, ρs, Ws, Hs;

The temperature of road pavement is determined by the equation of nonstationary thermal conductance [7] which makes it possible to consider for sharp variation of ambient variables and differences in thermal inertia properties of road structures made of various pavement layers studied in this work:

$$C\rho \ \frac{\partial T(x,t)}{\partial x} = \frac{\partial}{\partial x}\left[\frac{\partial T(x,t)}{\partial x}\right],$$

where $T(x,t)$ is the temperature in road structure of roadbed soil at the depth **x** at the time **t**.

Each pavement layer is characterized by certain thickness (H_i) and thermophysical properties (λ_i, c_i, ρ_i) which vary upon transition from one structure layer to another. Equation of thermal conductance can be written according to computations in the form of the set of linear equations with constant coefficients:

$$\{C_1 * \rho_1 * \frac{dT}{dt} = \frac{d}{dx} * \left({}_1 * \frac{dT}{dx}\right) ;\ C_2 * \rho_2 * \frac{dT}{dt} = \frac{d}{dx} * \left({}_2 * \frac{dT}{dx}\right) ;\ C_3 * \rho_3 * \frac{dT}{dt} = \frac{d}{dx} * \left({}_3 * \frac{dT}{dx}\right);\ C_n * \rho_n * \frac{dT}{dt} = \frac{d}{dx} * \left({}_n * \frac{dT}{dx}\right) \tag{1.1}$$

Boundary conditions are as follows:

1) Initial distribution of temperature in road structure will be presented as follows:

$$T_{(t=0)} = T_{(x,0)} = f_{1(x)} \tag{1.2}$$

2) Complex heat exchange takes place on pavement surface, which is determined by boundary conditions of the 2nd order applied for intensity of heat flow and of the 3rd order applied for heat exchange with ambient environment [8]. The boundary condition is as follows:

$$-\frac{\partial T(x,t)}{\partial x} = \alpha \cdot \left[T_{pav(t)} - T_{air(t)}\right] + \rho_{pav} \cdot q_{pav} \tag{1.3}$$

where ρ_{pav} is the coefficient of solar radiation absorption by road pavement; q_{pav} is the intensity of radiation falling on pavement, W/m^2

3) Let us preset boundary condition of the 4th order of layer boundaries determined by the equality of thermal flows and temperature at layer boundaries:

$${}_1 \frac{\partial T_1}{\partial x} = {}_2 \frac{\partial T_2}{\partial x}; T_1 = T_2 \tag{1.5}$$

4) The third boundary condition is based on the assumption of constant temperature at certain depth of attenuation of temperature oscillation amplitude:

$$T_{(H,t)} = T_d = const \tag{1.4}$$

Certain simplifications should be made for computations:

1) Thermophysical properties of road surface dressing materials do not depend on temperature, time, humidity and are constant in the layer boundaries.

2) Let us preset thermophysical properties of roadbed soil depending on its type and humidity according to the tables in [9], [10].

3) The coefficient of heat exchange will be determined by empirical equation recommended for prediction of temperature in road structure:

$$\alpha_k^{(1)} = 10.4 \cdot V_b^{0.7} + 2.2 \tag{1.6}$$

where V_b is the wind speed, m/s.

Krasnodar krai is located in the south of Russia and characterized by numerous sunny days including winter period. It is required to pay attention to accounting for cumulative solar radiation falling on road surface. The effect of solar radiation is expressed in significant increase in the temperature of road surface exceeding the air temperature T_{air}.

Procedures of consideration for solar radiation regarding this model were developed by Baklanov [11]

The influence of solar radiation on road pavement temperature is considered using the notion of equivalent ambient temperature [11]:

$$T_{eq} = p\frac{I}{\alpha_k} \tag{1.7}$$

where p is the coefficient of solar radiation absorption by road surface, I is the cumulative solar radiation upon high cloud amount of **n** points, W/m^2 which can be determined as follows [11]:

$$I = I_c \cdot [1 - (a_k - b_k \cdot n) \cdot n] \tag{1.8}$$

where a_k and b_k are the empirical coefficients; I_c is the cumulative solar radiation upon cloudless sky falling onto inclined road pavement surface.

Taking into account the influence of cumulative solar radiation on the temperature of road pavement in day time, the boundary Eq. (1.3) can be rewritten as follows:

$$-\frac{\partial T(x,t)}{\partial x} = \alpha \cdot \left[T_{pav(t)} - T_{c(t)}\right] \tag{1.9}$$

where Tc(t) is the temperature of air near pavement surface, °C:

$$T_{c(t)} = T_{air(t)} + T_{eq(t)} \tag{2.0}$$

Initial data for computations are as follows:

- Road surface dressing structure (number of layers, thermophysical properties and thickness of each layer);
- Thermophysical properties of road bed soil;
- Meteorological data: observations of meteorological stations of GKU Krasnodar Avtodor (air temperature, dew point, relative air humidity, wind speed).

C. Flow chart

Computational module for predicting temperature of roadbed and pavement layers was developed using Wolfram Mathematica software. It was based on the aforementioned mathematical model of temperature of roadbed and pavement layers with consideration for boundary conditions (Fig. 4).

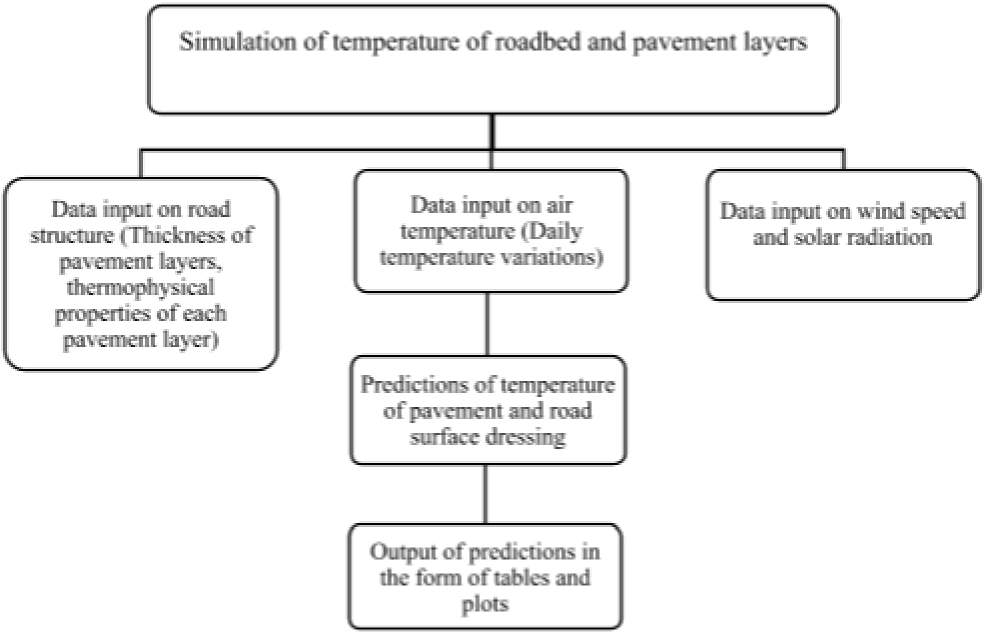

Fig. 4. Simulation of temperature regimes of road structures

The algorithm is comprised of several stages:
1. Entering data on road structure (thickness of pavement layers, thermophysical properties of each structure layer);
2. Entering data on air temperature (temperature variation in 24 hours);
3. Entering data on wind speed and solar radiation;
4. Predicting temperature of road pavement and pavement layers;
5. Output of predicted data in the form of tables and plots.

Simulation of temperature is performed on daily basis, data on air temperature, wind speed, and solar radiation are preset for every hour of computational period.

III. RESULTS AND DISCUSSION

Predicted temperatures of road pavement and pavement layers are recorded for every hour of calculation period. In order to verify calculations and to eliminate accumulation of errors, the increment across the structure depth was selected as follows:

- For pavement layers of asphalt concrete: 0.01 m;
- For foundation layers: 0.05 m.

Two structures of road surface dressing were selected for computational experiments (see Table I).

Table I. Variants of road surface dressing structures and thermophysical properties of pavement layers

Structure No.	Description	Layer thickness, m	Thermophysical properties		
			Density ρ_i, kg/m^3	Thermal conductivity λ_i, W/m*°C	Specific thermal capacity C_i, kJ/kg*°C
№1	Hot crushed stone dense fine-grained asphalt concrete, Grade I, Type A	0.05	2,400	1.40	1.65
	Hot crushed stone porous coarse-graded asphalt concrete	0.06	2,300	1.25	1.65

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	Hot crushed stone porous coarse-graded asphalt concrete	0.07	2,300	1.25	1.65
	Graded blast bound broken slag	0.20	800	0.19	1.10
	Ordinary blast furnace broken slag	0.24	800	0.19	1.10
	Roadbed soil (clay loam)	-	2,000	1.62	1.45
№2	Hot slag crushed stone dense fine-grained asphalt concrete, Grade I, Type A	0.05	2,320	0.39	1.68
	Hot slag crushed stone porous coarse-graded asphalt concrete	0.06	2,280	0.40	1.71
	Hot slag crushed stone porous coarse-graded asphalt concrete	0.07	2,280	0.40	1.71
	Graded blast bound broken slag	0.20	800	0.19	1.10
	Ordinary blast furnace broken slag	0.24	800	0.19	1.10
	Roadbed soil (clay loam)	-	2,000	1.62	1.45

Then the data are entered according to the described algorithm:

Number of layers int L = 5;

Thickness of layers H[] = { 0.05, 0.06, 0.07, 0.20, 0.24 };

Albedo _Rho0 = 0.9,

Coefficient of heat conductance lambda0[] = { 0.39, 0.40, 0.40, 1.1, 1.1};

Density rho0[] = { 2320, 2280, 2280, 800, 800 };

Coefficient of thermal capacity c0[] = { 1.68, 1.71, 1.71, 1.1, 1.1 };

Wind speed aWb[] = { 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 2, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1 };

Calculation period Ts = 24;

Air temperature dayT[]= {6, 6.3, 6.4, 6.8, 6.6, 5.8, 5.4, 5.2, 5, 4.8, 4.0, 4.0, 3.3, 3.1, 0, -2, -3.5, -5, -1.3, 0.5, 1, 1.7, 2.5, 3};

After calculations according to the described algorithm, we obtain temperatures for Structure 1 and Structure 2:

TL 1 – temperature on pavement surface;

TL 2 – temperature at the depth of 5 cm from pavement surface;

TL 3 – temperature at the depth of 11 cm from pavement surface.

Simulation results are illustrated in Fig. 5:

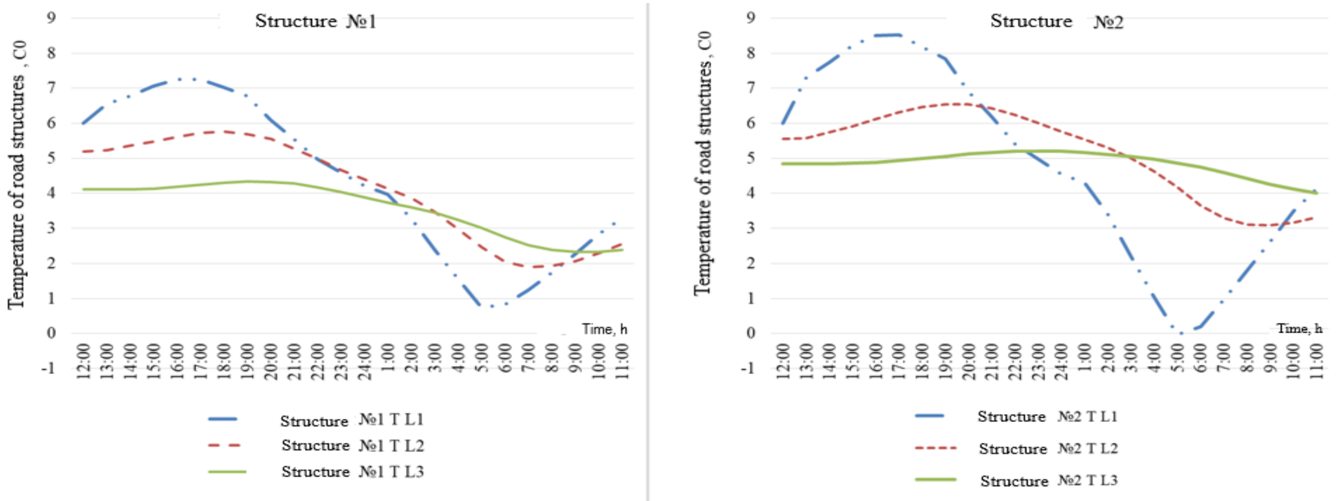

Fig. 5. Simulation of temperatures of the considered structures

The authors developed the procedure of computational experiment. The experiments provided data describing temperature regime of road structures. Analysis of the simulation results has demonstrated that upon given meteorological conditions, the temperature of pavement surface for Structure 1 T_1 = 7.26°C was lower than that of Structure 2: T_2 = 8.51°C. In addition, it should be mentioned that the temperature of the second layer L_2 was higher for Structure 2, which confirmed the results in [2]. The obtained data confirm that the efficiency of heat exchange and accumulation of thermal energy in multilayer structure can be adjusted by varying thermal conductance of asphalt concrete layers and their positions in road structure [2], [3]. Agreement of the obtained results with the experiments [2], [3] makes it possible to state that the selected model estimates adequately temperature regime in road structure as well as precise temperature both on pavement surface and deep in road structure.

IV. CONCLUSION

The obtained results can be applied for simulation of temperature regimes of various road pavements in the considered region, for estimation of hazard of winter slipperiness on various road pavements and for decreasing the number of winter slipperiness cases on road pavement due to application of road structures with certain thermophysical properties.

The following tasks will be solved:

- Determination of peculiarities of winter slipperiness formation in transition period as well as during sharp short-term night drops of air temperature;
- Comparison of temperature regimes of various road structures under similar meteorological conditions.
- Estimation of possibility to decrease the number of cases of zero crossing temperature of pavement in winter in Krasnodar krai during sharp drops of air temperature.

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