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Prediction of temperature distribution in asphalt concrete layers

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Abstract. The paper is devoted to the issues of predicting the temperature distribution in asphalt concrete layers in different periods of the year. Mechanical parameters of asphalt concrete strongly depend on its temperature. The reliability of the temperature dependence used for temperature prediction directly determines the reliability of calculation methods for motorway pavements design. At the same time, it should be noted that many existing models describe the temperature distribution along the depth of the asphalt concrete layer package with a rather large degree of error and are not calibrated for the conditions of the Russian Federation. Methods. The approach proposed by the authors is based on the study of the actual temperature distribution in asphalt concrete pavements by analyzing data from a set of measuring sensors installed at different depths of the asphalt concrete pavement package. The actual temperature distribution was monitored during the annual cycle from March 2023 to April 2024. Results. To approximate the results obtained, a dependence describing the sinusoidal nature of temperature variation on the surface and in the asphalt concrete layers was modified. Modification of the dependence was carried out by introducing an additional empirical parameter characterizing the dependence of the change in the absolute temperature value on the depth. The accuracy of the modified dependence is confirmed by the root mean square error (RMSE) value of up to 10 %. Conclusions. The model modified in the paper can be used at the stage of design and operation of motorways when calculating the temperature conditions of asphalt concrete layers.

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1. Introduction

The mechanical properties of asphalt concrete pavements depend to the greatest extent on temperature. Correct consideration of temperature will significantly increase the reliability of designing asphalt concrete pavements of motorways. At the same time, both prediction of temperature during the year and prediction of its change in the depth of asphalt concrete layers are important. Thus, **the main object** of this research is the temperature distribution along the depth of asphalt concrete pavements during the annual cycle. All the models for accounting for the temperature of functioning of asphalt concrete layers are divided into three groups. The first are the models that relate air temperature and other factors with the pavement temperature; the second are the models predicting the pavement temperature in the annual cycle; and the third are the models predicting the temperature variations in the depth of asphalt concrete layers. Many specialists have devoted their works to the problem of investigating the temperature of asphalt concrete layers depending on the ambient temperature. In particular, B.B. Teltayev conducted comprehensive studies of the water-thermal regime of pavements of the highways of the Republic of Kazakhstan [1, 2]. In his works, new results were obtained concerning changes in the nature of temperature distribution along the depth of the pavement in summer and winter periods, and also the possibility of deviation of temperature changes from the quasi-harmonic regime in cold periods of the year was revealed.

At the same time, it is the quasi-harmonic regime of change in air temperature and, consequently, pavement temperature that underlies the modern ideas about temperature modes of asphalt concrete performance. An extensive analysis of existing models describing temperature changes on the surface and in asphalt concrete layers is presented in [3]. In this paper, the models describing the temperature regime of asphalt concrete layers were divided into three groups: based on numerical methods, analytical solutions, and statistical information. At the same time, in a number of works, equations describing temperature changes are divided by time of day [4, 5], for example, into “pave rising” and “pave falling” dependencies. The papers [4, 5] analyse the factors affecting the temperature distribution in road structures in general and in asphalt concrete layers and describe the main factors used in the construction of such models.

Despite the variety of such models, the main interest is undoubtedly represented by the models underlying mechanistic-empirical methods of calculation of road structures [6–9]. The method of predicting the temperature distribution in pavement layers set out in the Mechanistic-Empirical Pavement Design Guide is based on the solution of the heat conduction equation. Models based on this solution are called Climatic-Materials-Structural (CMS) [10, 11] and Cold Regions Research and Engineering Laboratory (CRREL) [12–14] models. The solution of the one-dimensional heat conduction equation is carried out using a finite difference method. The boundary condition at the upper boundary is the air temperature parameters at the pavement surface and at the lower boundary is a node with constant temperature maintained by infinite heat inflow. The CRREL model also predicts the depth of ground freezing and thawing.

In addition to complex analytical methods, a number of regulatory documents and scientific and technical literature contain simpler but no less effective engineering methods that allow taking into account the temperature of asphalt concrete layers. To calculate the pavement temperature as a function of air temperature, the Ladygin equation can be used as follows [15]:

$$T_{as} = 1.3 * T_{air} + 7, \quad (1)$$

where T_{as} is the asphalt surface temperature; T_{air} is the air temperature;

A more complex dependence, taking into account, besides air temperature, solar radiation and albedo of the coating surface, was obtained by Ya.N. Kovalev [16]:

$$T_{as} = \frac{J(1-A)k_w}{\alpha_c} + T_{air}, \quad (2)$$

where J is calculated flux of total solar radiation; A is the surface albedo; α_c is the total heat transfer coefficient at the coating-air interface; k_w is the coefficient depending on wind speed.

RDO Asphalt 09 uses a logarithmic law of temperature variation along the depth of asphalt pavements. The proposed relationship is as follows:

$$y = b\ln(0.01x + 1.0) + T, \quad (3)$$

where y is the temperature, °C, on depth x, cm; b is the parameter, depending on T; T is the temperature on surface pavement.

Various dependencies are also used to predict the temperature variation on the pavement surface depending on the air temperature. As noted in [17], the dependence of pavement temperature fluctuations has a cyclic character and can be approximated by a sinusoidal function:

$$X = X_0 + X_m \sin(\omega T); \\ \omega = 2\pi/T_0, \quad (4)$$

where X is the surface temperature; X_0 is the seed temperature value; X_m is maximum amplitude of temperature fluctuation; ω is the cyclic frequency; T_0 is the number of time units in a year (if a day is taken as a time unit, then T_0 = 365); T is a particular point in time (day) from the initial condition of the process.

In particular, the Gaivoronsky formula [18] is one of the special cases of the presented dependence:

$$T_s = T_{air} * \left[1.5 + 0.5 * \cos \frac{\pi * (n-7)}{6} \right], \tag{5}$$

where T_s is the surface temperature, °C; T_{air} is the air temperature, °C; n is the ordinal number of the month starting with January.

Thus, we can state a large number of works concerning the temperature of asphalt concrete pavements during the annual cycle. At the same time, the problem of correct choice of dependencies for predicting the temperature of asphalt concrete pavement on the surface and temperature distribution along its depth remains open, which is confirmed by the lack of a unified approach [19–23]. In particular, within the Mechanistic Empirical Design Procedure, which is the most relevant at the moment, the temperature-moisture databases are updated and updated annually, as well as the dependencies used by different regions in their practical activities [24–27]. Moreover, obtaining reliable data on the temperature in asphalt concrete layers and models for its prediction is also of interest to researchers dealing with the problems of asphalt concrete damageability, using the principles of deformation or energy equivalence of continuous and damaged media [28, 29]. Since 2022, air temperature and humidity monitoring stations have been installed in three road-climatic zones of the Russian Federation – II, III, IV.

The objective of the study is to modify an empirical model for predicting the temperature distribution along the depth of asphalt concrete pavements based on field data. In order to achieve this objective, the following tasks are solved:

- equipping the road structure under construction with temperature sensors located at different depths;
- constructing graphs of changes in temperature regimes of asphalt concrete pavements during the annual cycle;
- constructing calculated dependencies of asphalt concrete temperature changes at different depths;
- comparing in-situ and experimental dependencies of temperature changes by depth of asphalt concrete layers;
- modifying dependencies for prediction of temperature changes by depth of asphalt concrete layers providing the greatest correspondence of calculated and experimental data.

2. Methods

An experimental site for studying the temperature and humidity regime of asphalt concrete layers was organized in the III road-climatic zone on the M5 Federal "Ural" highway, the route of which passes through Moscow – Ryazan – Penza – Samara – Ufa – Chelyabinsk, on the section km 286+000 – km 297+000 (Fig. 1). Temperature sensors were installed at different depths in the asphalt concrete layers of the new road structure. The pavement design is presented in Table 1.

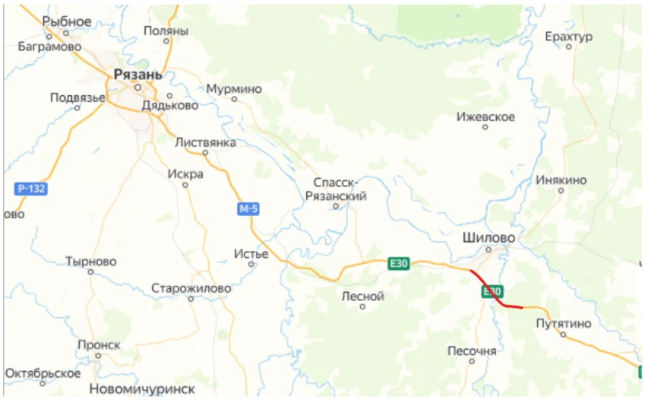


Figure 1. Experimental site.

Table 1. Pavement on monitoring station.

№ layer		Layer name	Thickness, cm
Asphalt surface	1	SMA-16	5
	2	А22Нт (Lower layer of asphalt concrete pavement)	7
Base	3	А32От (Upper layer of asphalt concrete pavement)	10
	4	Gravel fraction 31.5–63 mm	32
	5	Fine sand with dusty particles content of 5 %	35
Soil	6	Heavy dusty loam	-

Digital temperature transducers – sensors placed in metal sleeves – are used for temperature recording. Each sensor sleeve has a polymer coating to prevent freezing to the borehole walls. Sensors are connected with fire-resistant cable with reduced smoke and gas emission, resistant to chemically aggressive media and retaining its flexibility at operating temperatures down to –60 °C.

Temperature measurement range was from –60 to +85 °C. Instrumental measurement error was ±0.1 °C over the entire range.

The temperature sensors were installed as follows. After laying the pavement layer, a hole was drilled to the full depth of the finished asphalt concrete layer package, and a groove was made from the hole to the edge of the asphalt concrete layers for laying the cable running from the sensors to the data processing and storage device. After all the necessary holes were made and cleaned, the temperature sensors and data transmission cable were lowered into them. Then they were filled with heated bitumen and sealed with cold asphalt. The scheme of sensor location in the asphalt concrete layers is shown in Fig. 2.

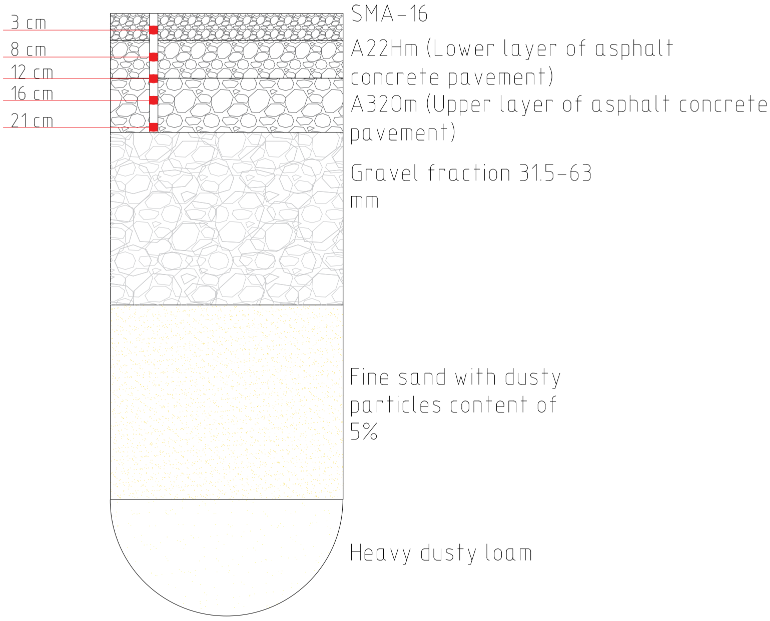


Figure 2. Layout of temperature sensors in the asphalt concrete layers.

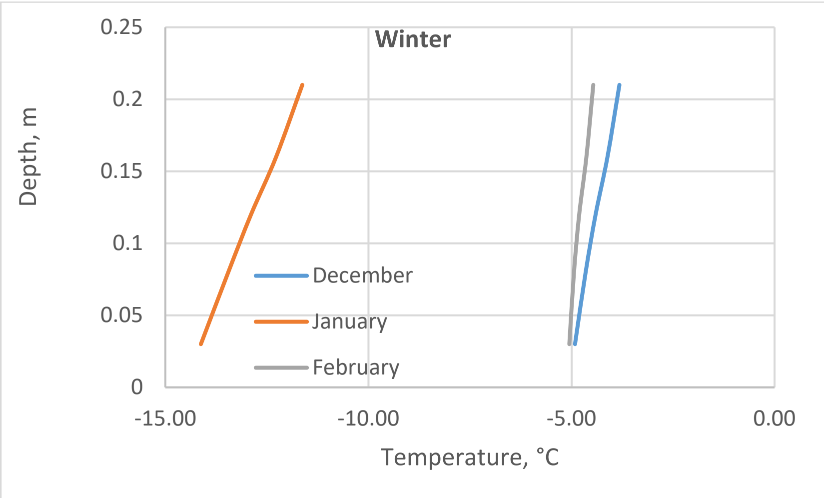
3. Results and Discussion

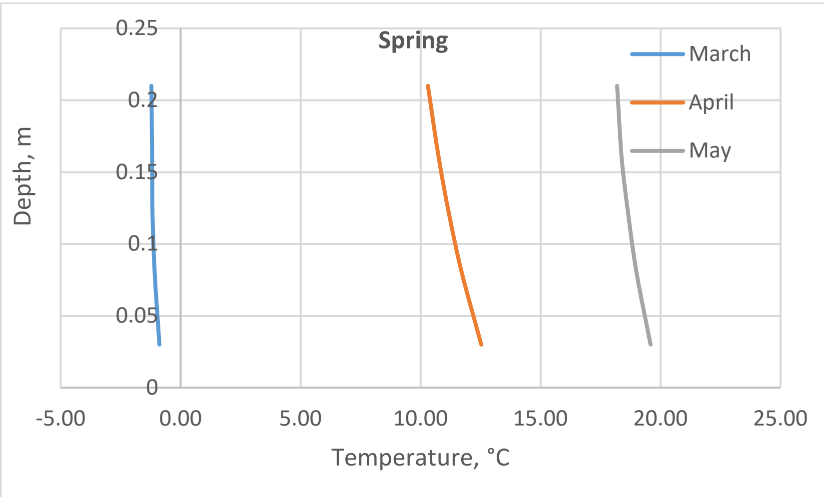
Temperature monitoring from March 2023 to April 2024, resulted in monthly average air and asphalt pavement layer temperatures (Table 2).

Table 2. Monthly average temperature data.

Month number	Measuring time	Air temperature, °C	Temperature of asphalt concrete at depth, °C				
			0.03 m	0.08 m	0.12 m	0.16 m	0.21 m
5	May	14.42	19.58	19.00	18.66	18.38	18.19
6	June	18.17	24.63	24.17	23.94	23.76	23.67
7	July	20.55	25.54	25.07	24.83	24.64	24.55
8	August	20.04	24.64	24.39	24.31	24.26	24.28
9	September	14.21	16.27	16.25	16.30	16.39	16.52
10	October	5.53	6.64	6.80	6.97	7.19	7.41
11	November	0.61	1.55	1.74	1.93	2.15	2.37
12	December	–2.17	–4.91	–4.65	–4.41	–4.11	–3.82
1	January	–11.30	–14.13	–13.45	–12.89	–12.27	–11.63
2	February	–5.79	–5.05	–4.94	–4.81	–4.63	–4.46
3	March	–2.68	–0.89	–1.08	–1.17	–1.19	–1.22
4	April	10.68	12.53	11.72	11.19	10.75	10.31

A graphical representation of the pavement temperature values measured at different depths by seasons is presented below (Fig. 3).





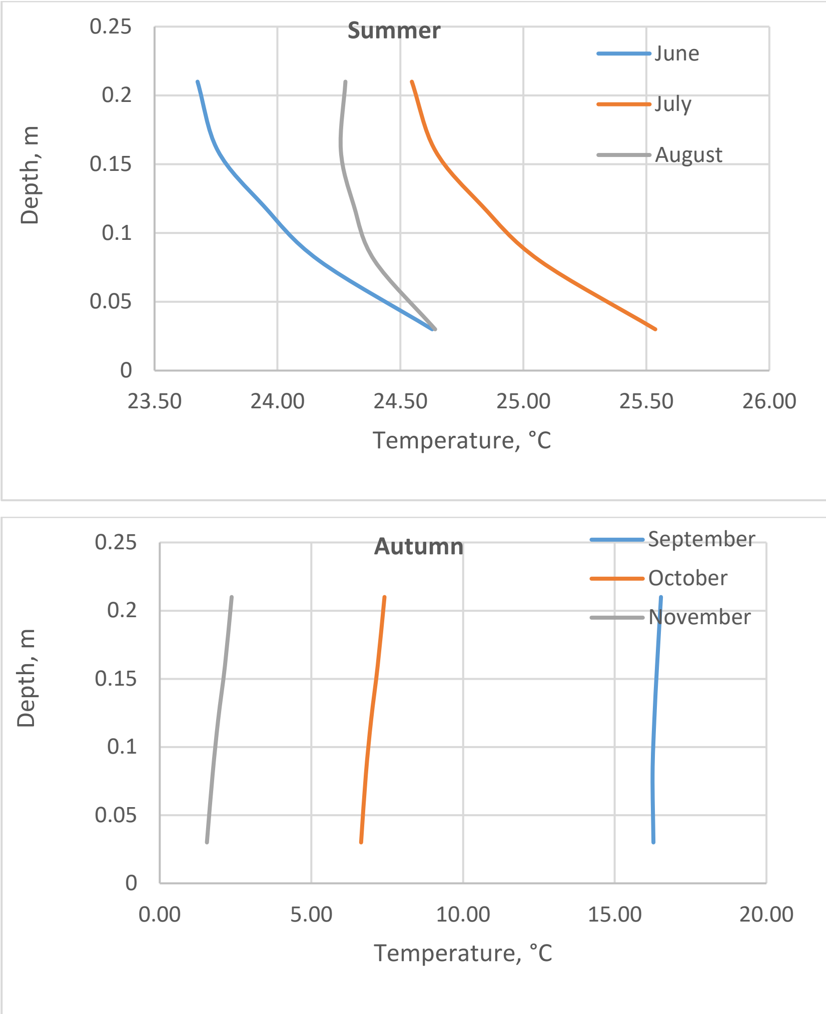


Figure 3. Dependence of changes in average monthly temperatures of asphalt concrete layers at different depths by seasons of the year.

Analyzing this graph, it is necessary to note the changing nature of dependencies characterizing the actual values of temperatures of asphalt concrete pavement layers at different depths. Thus, the dependences of temperature changes in winter, spring, and autumn periods are generally close to the linear form. The dependence characterizing the summer period has a sharply nonlinear, parabolic nature. It can be assumed that the similar dependence for extreme summer temperatures will have even more pronounced nonlinearity (Fig. 4).

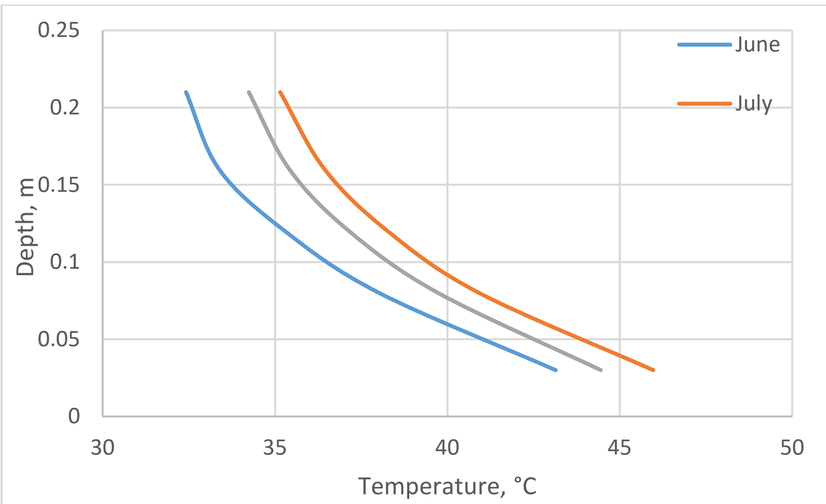


Figure 4. Dependence of changes in extreme temperatures of asphalt concrete layers at different depths in the summer period.

The data obtained were used to verify the formulas presented in the Mechanistic Empirical Guide for determining the temperature of asphalt concrete pavement based on air temperature, as well as for determining the temperature at different depths using formulas (3) and (5). The values of the parameter *b* are given in Table 3, and correspond to the RDO Asphalt 09.

Table 3. Dependence of the parameter b on the surface temperature.

T, °C	<–10	<–5	<0	<5	<10	<15	<20	<25	<30	<35	<40	<45	>45
b	6.5	4.5	2.5	0.7	0.1	0.3	0.4	–1.6	–4.0	–6.2	–8.5	–10.5	–12.0

Based on the calculation results, graphs of calculated and actual temperatures of asphalt concrete pavement at different depths were plotted and compared, the graphs are presented in Fig. 5.

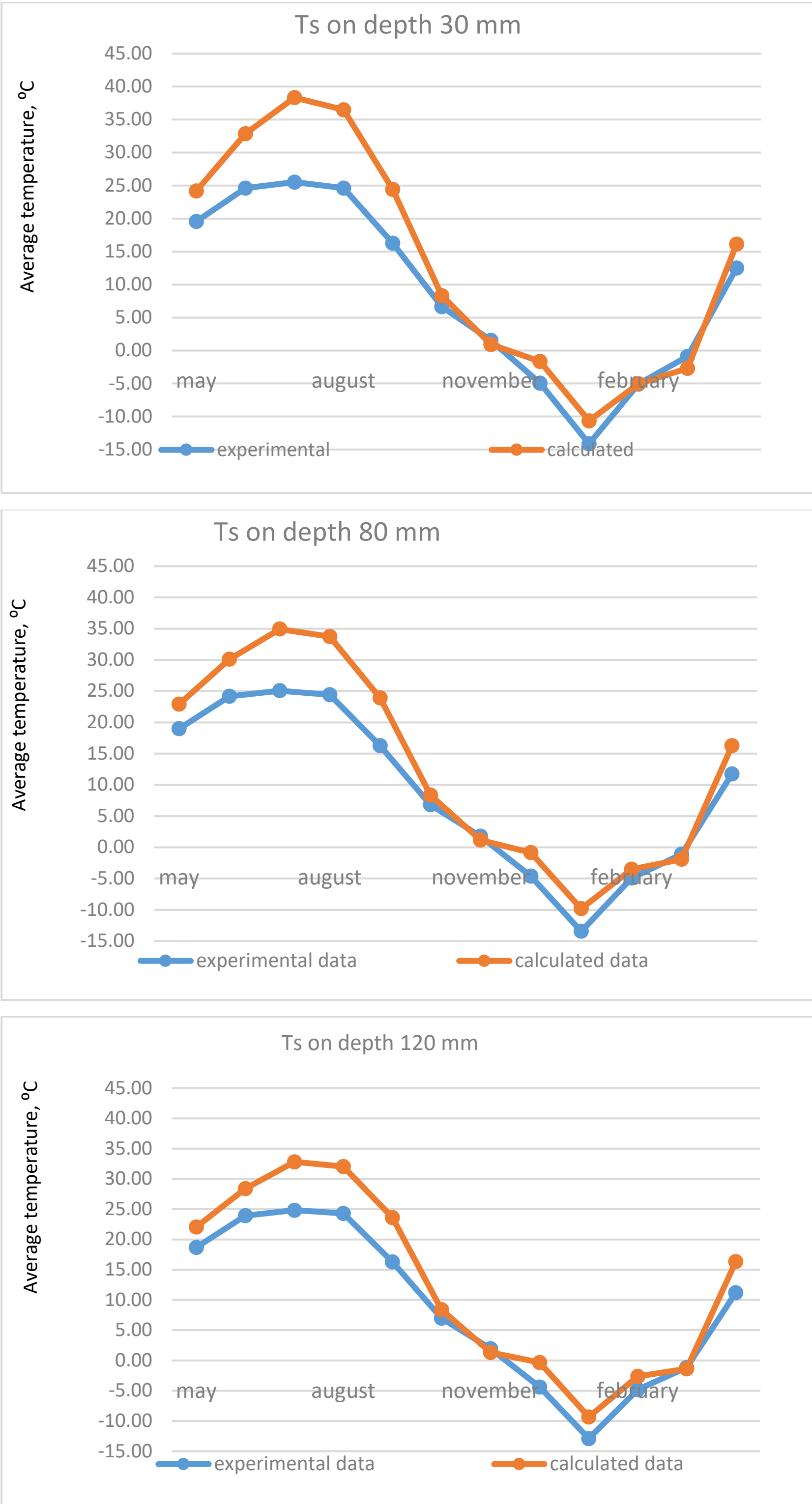


Figure 5. Comparison of calculated asphalt concrete temperature values with actual values at different depths.

To assess the convergence between the calculated and experimental temperatures, the root mean square error (RMSE) was calculated:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{t_{calc} - t_{\exp}}{t_{\exp}}\right)^2}, \tag{6}$$

where $t_{\exp}$ is the experimental temperature value; t_{calc} is the calculated temperature value.

The results of the standard deviation of the error are shown in Table 4.

Table 4. RMSE values.

Sensor depth, m	RMSE, %
0.03	60
0.08	19
0.12	1
0.16	14
0.21	29

As can be seen from the table, the best correspondence between the calculated and experimental data is achieved at a depth of 0.12 m. In other cases, the difference between calculated and measured values can reach 60 %.

In order to minimize the RMSE index, the selection of b coefficients for formula (2) was carried out. However, in this case, when approaching the temperature graph for one of the investigated depths, a greater deviation of the calculated temperature from its actual value measured at other depths was observed. To eliminate this problem, dependence (2) was modified to the form:

$$y = b\ln\left(0.01h + m\left(h\right)\right) + T_s, \tag{7}$$

where $m\left(h\right)$ is a function that takes into account the variation of the additional empirical parameter m from depth in temperature prediction.

Selection of coefficients b in the first approximation was made for the average depth, at which the actual temperature of asphalt concrete is known. The values of this coefficient, at which the graphs of the calculated temperature and the actual measured temperature at a depth of 0.12 m completely coincided with an accuracy of 2 %, are shown in Table 4. Fig. 6 shows the curves of calculated and actual temperature at a depth of 0.12 m from the top of the pavement (Fig. 6, Table 5).

Table 5. Selected values of the dependence of the parameter b on the surface temperature.

T, °C	*b*
–15	–4.25
–10	–1.23
–5	1.78
–2.5	–2.99
0	1.79
5	–0.31
10	–2.66
15	–5.53
20	–8.25
<25	–10.95
>25	–7.63
30	–11.55
35	–15.48
40	–19.4
45	–23.32

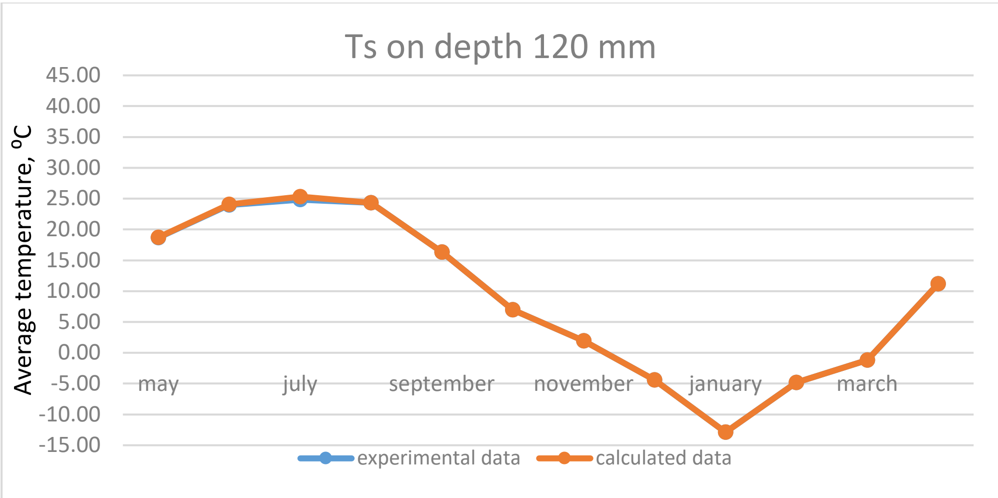


Figure 6. The result of fitting the parameter *b* for the temperature recorded at 0.12 m depth.

At the next stage, the dependence of the index m on the change of asphalt concrete depth was selected. Thus, having data on asphalt concrete temperatures at the depths of 0.03, 0.08, 0.12, 0.16 and 0.21 m, it was possible to determine the following values of the index m (Table 6).

Table 6. Selected values of dependence of parameter m on asphalt concrete depth.

Depth, cm	<5	<10	<15	<20	<25
m	2	1.5	1	0.5	0

The results of applying the selected dependencies with the selected values of m and b are shown in Figs. 7–10.

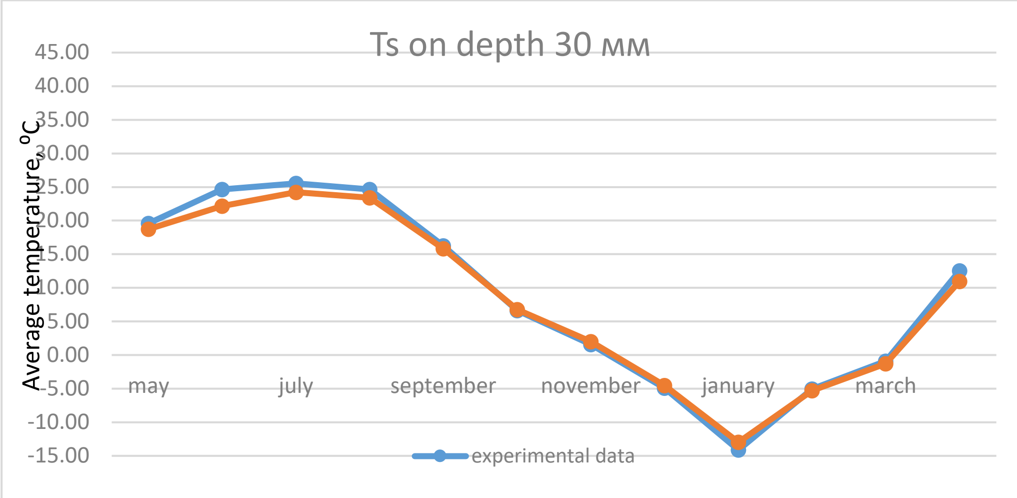


Figure 7. Calculation result using the parameters *b* and *m* for the temperature recorded at a depth of 0.03 m.

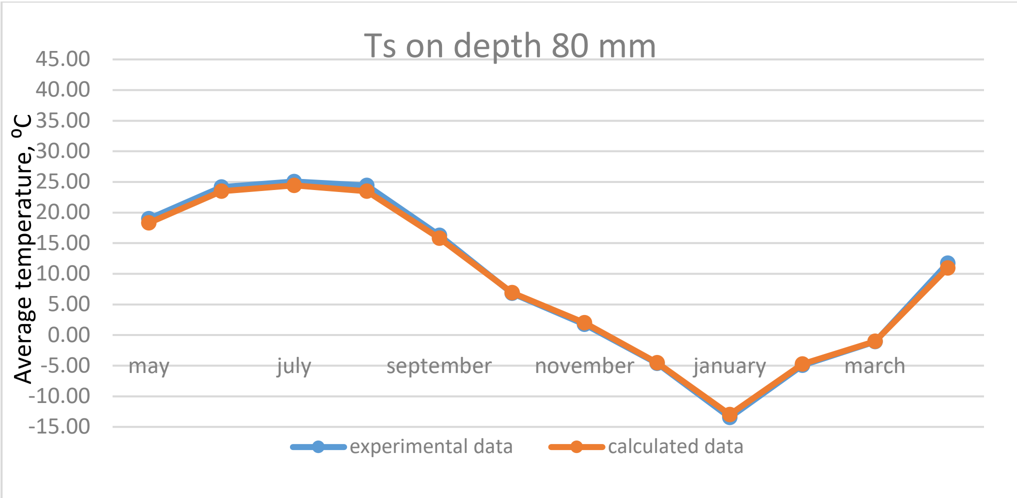


Figure 8. Calculation result using the parameters *b* and *m* for the temperature recorded at a depth of 0.08 m.

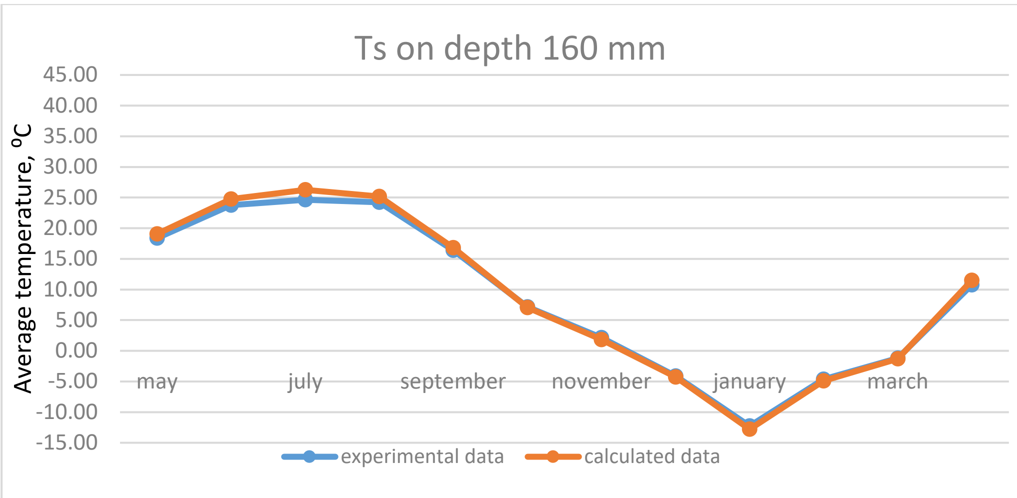


Figure 9. Calculation result using the parameters *b* and *m* for the temperature recorded at the depth of 0.16 m.

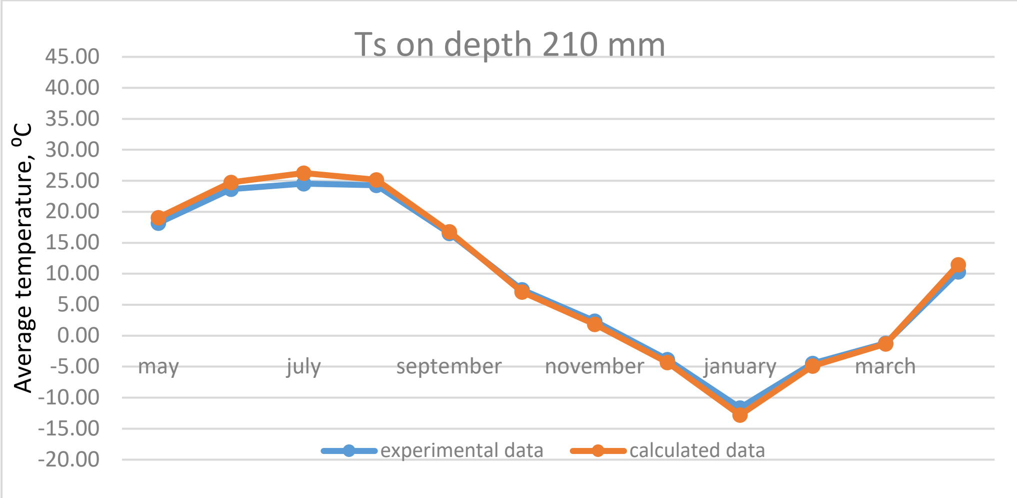


Figure 10. Calculation result using the parameters *b* and *m* for the temperature recorded at a depth of 0.21 m.

The values of the RMSE index based on the results of analyses of dependencies with selected coefficients are shown in Table 7.

Table 7. RMSE values.

Sensor depth, m	RMSE, %
0.03	10
0.08	5
0.12	1
0.16	6
0.21	9

Thus, the choice of the dependence of the parameter b on the pavement temperature and introduction of the function $m(h)$ made it possible to achieve the most accurate results in predicting the variation of design temperatures along the asphalt concrete depth. In the future, it is planned to accumulate more data with different variation of average and median values of monthly air and asphalt concrete temperatures in different road-climatic zones, as well as measurements with a large variation in depth, which will make it possible to correct the obtained dependencies.

However, for the case under consideration it is already obvious that the accuracy of the modified model will significantly exceed the accuracy of the standard RDO Asphalt 09 model and Gaivoronsky model [18], the deviation of which from the field data registered at the survey site will be from 1 to 60 %. Other models, such as the Ladygin model [15] and the Kovalev model [16], will also provide only a fragmentary match between the theoretical curves of temperature change and the experimentally measured data.

The efficiency of implementation of more complex models based on the solution of differential heat conduction equations CMS [10–11] and CRREL [12–14] will also require the development and introduction of a number of empirical coefficients and should be considered only after obtaining a large sample of data for II–IV road-climatic zones. In general, it can be stated that the modified model in this paper has a good level of fit to the experimental data.

4. Conclusion

1. The applicability of a set of dependencies for predicting the temperature distribution in asphalt concrete layers and during the annual cycle of pavement operation has been substantiated, providing a good correspondence with the results of experimental observations carried out in the conditions of III road-climatic zone at the monitoring station of temperature and humidity regime of the exploited motorway.
2. Modification of the RDO Asphalt 09 dependence for predicting temperature by depth of asphalt concrete pavement package has been performed. The formula is modified by introducing the

function $m(h)$ characterizing the change of the empirical parameter m from the depth, at which the prediction is carried out.

3. The dependence is verified on a set of empirical data on the temperature changes on the pavement surface and in the depth of the asphalt concrete layer package, obtained from a stationary observation point for temperature and humidity regime on the section of the M5 Federal "Ural" highway, the route of which passes through Moscow – Ryazan – Penza – Samara – Ufa – Chelyabinsk, km 286+000 – km 297+000.
4. A good correspondence between the calculated results of temperature prediction on the pavement and in asphalt concrete layers and experimental measurements was proved. The RMSE was considered as a criterion of compliance. It was found that when standard dependencies are applied, the maximum RMSE value is 60 %. When using modified formulas, the RMSE will be up to 10 %.

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