

# Comparison of temperature distributions in road pavement obtained in field tests and using transient thermal analysis

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**Abstract.** The paper presents the results of comparative analyzes of temperature distributions in the pavement structure. The distributions were determined in field measurements and transient thermal analysis. The phenomenon of thermal conduction in a road pavement is described by the Fourier-Kirchhoff heat transfer equation. The temperature distribution was analyzed at several depths of the pavement structure. The results of calculations are presented in the form of temperature profiles and graphs of temperature variability. The heat transfer model applied in the qualitative aspect correctly shows the heat transfer in the pavement structure, however in quantitative terms it requires calibration to local climatic and material conditions. Knowledge of the temperature distribution in the pavement is very important for the design and mechanical analysis of pavement structure.

## 1 Introduction

Asphalt pavements in the Polish climate are exposed to high temperature changes. In combination with loads from the wheels of heavy vehicles, this causes difficulties during the design, construction and exploitation. In recent years, one can observe great progress in the field of research and analysis related to pavement thermal behavior. For example, procedures for testing the low-temperature properties of asphalt mixtures (HMA) have been introduced [1]. There are also numerous field observations using roadside meteorological stations. Using the results of such tests and measurements, numerous analyzes are carried out on pavements taking into account thermal factors [2-12].

Analyzes concerning the adaptation of test methods and requirements for road bitumens to the actual thermal conditions in which bitumens work in road pavements in Poland were conducted by Pszczola et al. in [2]. It was reported that currently in the European Union, road bitumens are most often classified on the basis of penetration testing results. Such an approach does not reflect the climatic conditions in which the pavement with the tested bitumen work. It has been suggested to choose bitumen depending on the location of the road in a particular climate zone in Poland.

Górszczyk and Grzybowska presented the results of the heat transfer simulation in the road pavement in [7]. It was shown that the Fourier-Kirchhoff thermal conduction law well describes the phenomenon of heat conduction in a multi-layer pavement structure. Its formulation in FEM can be used to determine the temperature distribution.

Graczyk et al. proposed a new analytical solution for the problem of flow and heat refraction in a multilayer

pavement in [8]. It was found that solar radiation is a very important climatic factor that acts directly on the top layers of the pavement. It causes a rise in temperature and the formation of an additional temperature gradient in the multilayer structure. It was also shown that the temperature field in the pavement significantly depends, for example, on the geometry of the layer system, thermal characteristics of the upper and lower layers and the color of the wearing layer.

Conducted analyzes influence the design and quality of built-in asphalt mixtures and enable the development of knowledge related to heat transfer in road pavement structures.

At the stage of road pavement design, knowledge about local climatic conditions should be used. This promotes an individual approach to the design process using the mechanistic-empirical method. Such solutions can generate increased costs at the design stage. However, taking into account economic aspects included in the entire life cycle of the structure, such an approach ultimately brings significant benefits.

This article presents the results of comparative analyzes of temperature distributions in the structure of road pavement. The distributions are determined in field tests and transient thermal analysis by using the heat equation. The temperature distribution is analyzed at several depths of the pavement structure. A road section located on the A4 motorway, near the Targowisko I node located in the Małopolskie voivodship, is selected for the measurements and analysis.

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## 2 Analyzed cross-section and field measurement method

### 2.1 Characteristics of the analyzed road cross-section

The analyzed road cross-section has two lanes in each direction and a hard shoulder for emergency stop. The width of each lane is 3.75 m, and the width of the emergency lane is 3.0 m. On the other hand, the width of the ground shoulders is 1.25 m. The carriageways are separated by the soft separating strip with a width of 5.0 m,

The vertical alignment of the road is located in a cut about 3 m deep. The longitudinal gradient does not exceed 1%. The road is located in an area with small height differences. The analyzed road section is mostly surrounded by agricultural areas, covered with low vegetation, with a small number of trees.

The pavement structure is adapted to carry loads of 115 kN / axle. The upper layers of the structure are made as asphalt layers. The 4cm thick wearing layer is the stone mastic asphalt (SMA) with the maximum grain size of the 11mm. Below it is a binding layer 8cm thick made of asphalt concrete (AC 20). Then the base layer is also made of asphalt concrete (AC 25), 19 cm thick. They are laid on unbounded, mechanically stabilized base layer. The subbase is a layer of mineral aggregate with a thickness of 40 cm, with a grain size of 0/31.5 mm and CBR > 60%. The antifrost layer is a layer of aggregate with a thickness of 40 cm and a CBR > 35%.

### 2.2 Field measurement method

Field measurements are carried out by a meteorological station near Krakow [13]. The basic parameter measured by the station is temperature. The temperature measurement consists in measuring the resistance of the resistor and converting it to the temperature. To measure the resistance, two, three or four wire measurements are made to compensate for the resistance of the conductors. Temperatures are measured at the following measuring points:

1. 2m above the surface of the road pavement structure,
2. on the surface of the road pavement structure,
3. 5cm below the surface of the road pavement,
4. 30cm below the surface of the road pavement structure.

The air temperature is measured at a height of two meters above the surface of the pavement structure. Subsequent measured temperatures are the temperatures of the pavement structure layers. In the analyzed case, these are the temperatures of the asphalt layers. The temperature at a depth of 5cm below the surface of the pavement is the temperature of the binding layer. The lowest placed sensor is located 1 cm above the bottom of the asphalt layers. It measures the temperature of the asphalt concrete base layer.

## 3 Transient Thermal Analysis

The temperature of the system is a measure of its heat or internal energy. The system temperature increases as a result of energy supply. There are three basic modes of heat transfer: by convection, conduction and electromagnetic radiation. Conduction of heat occurs when energy transfer occurs through the interaction of atoms and body molecules, but the atoms themselves are not transferred. During convection, heat transfer involves the transfer of medium. In contrast to conduction, where the medium was not transferred and the energy changed only through interacting molecules [9].

A completely different heat transfer mechanism creates heat radiation. It is not related to the transport of the medium, but it occurs through the emission or absorption of electromagnetic waves.

There are three basic modes of heat transfer in the asphalt pavement: thermal convection, thermal conduction and thermal radiation. The heat flow balance  $\Phi$  on the surface of the asphalt pavement can be expressed by the following equation (1)[14]:

$$\Phi = \Phi_S + \Phi_{Atm} - \Phi_{OF} \pm \Phi_C \pm \Phi_{WL} \quad (1)$$

where:

$\Phi_S$ —heat flow caused by shortwave solar radiation [W],

$\Phi_{Atm}$ —heat flow caused by longwave radiation of the atmosphere [W],

$\Phi_{OF}$ —heat flow caused by longwave self-radiation of the asphalt pavement [W],

$\Phi_C$ —heat flow caused by convection [W],

$\Phi_{WL}$ —heat flow caused by conduction [W].

The effect of these phenomena is variable temperature distribution in the pavement, which has a significant impact on the pavement performance.

In the asphalt pavement, heat transfer occurs only through conduction, the intensity of which depends on the surface temperature of wearing course. Changing weather conditions cause different heat flows in the pavement structure. Not only the value of the heat flux changes, but also the direction that is dependent on the temperature profile in the asphalt pavement. This is because heat transfer occurs from higher to lower temperatures.

Thermal conduction is defined by Fourier's Law of Conduction (2):

$$q = -\lambda_n \cdot \frac{\partial \vartheta}{\partial n} \quad (2)$$

where:

$q$  – heat flux in direction n [W/m<sup>2</sup>],

$\lambda_n$ — thermal conductivity in direction n [W/m·°C],

$\frac{\partial \vartheta}{\partial n}$ — thermal gradient in direction n [°C/m],

$\vartheta$ —temperature [°C].

It is assumed that the asphalt mixture is homogeneous and isotropic and has a thermal conduction coefficient independent of temperature. With these assumptions, the temperature distribution inside the asphalt pavement can be obtained by solving the heat equation (3):

$$\frac{\partial \vartheta}{\partial t} - \frac{\lambda_w}{\rho \cdot c_p} \cdot \left( \frac{\partial^2 \vartheta}{\partial x^2} + \frac{\partial^2 \vartheta}{\partial y^2} + \frac{\partial^2 \vartheta}{\partial z^2} \right) = 0 \quad (3)$$

where:

$\vartheta$  – temperature [°C]

$\lambda_w$  – thermal conductivity [W/m·°C]

$\rho$  – mass density [kg/m<sup>3</sup>]

$c_p$  – specific heat capacity [J/°C·kg]

Simplifying the differential equation (3) by removing from the analyzes the width and length of the road pavement structure, obtaining the equation (4) determining the temperature distribution in the pavement structure depth:

$$\frac{\partial \vartheta}{\partial t} = \frac{\lambda_w}{\rho \cdot c_p} \cdot \left( \frac{\partial^2 \vartheta}{\partial x^2} \right) \quad (4)$$

If the time and variable x are divided into small intervals then the differential equation (4) can be expressed in the form of a discrete differential equation (5), in which:  $\partial \vartheta \approx \Delta \vartheta$ ,  $\partial x \approx \Delta x$ ; (explicitly method) [9]:

$$\frac{\Delta \vartheta}{\Delta t} = \frac{\lambda_w}{\rho \cdot c_p} \cdot \left( \frac{\Delta^2 \vartheta}{\Delta x^2} \right) \quad (5)$$

$$\Delta \vartheta = \vartheta_{n,k+1} - \vartheta_{n,k}$$

$$\Delta \vartheta = \vartheta_{n+1,k} - \vartheta_{n,k}$$

$$\Delta^2 \vartheta = \vartheta_{n+1,k} - 2\vartheta_{n,k} + \vartheta_{n-1,k}$$

To ensure the numerical stability of calculations, a condition was defined which determined the relationship (6) between the increase in distance and time [9]:

$$\frac{\lambda_w}{\rho \cdot c_p} \cdot \left( \frac{\Delta t}{\Delta x^2} \right) \leq \frac{1}{2} \quad (6)$$

To solve the equation (4), boundary conditions must be known:

- surface temperature of the road asphalt pavement,
- temperature at the bottom of the road pavement,
- vertical temperature profile at the moment of starting calculations.

In order to determine the boundary conditions, the surface temperature of the pavement structure is necessary. To solve the problem of thermal balance (1), climate parameters, the location of measurement stations and the years in which the tests were carried out must also be known. For the calculations made, the surface temperature of the wearing course was taken from field measurements [13].

As the second boundary condition, instead of the temperature at the bottom of the last layer of the pavement, the soil temperature was assumed at a depth of -2.5 m under the pavement surface. The temperature at this depth was determined as constant and equal to the average temperature during the year. For these calculations it was equal to 8 °C.

Equation (7) shows periodic changes in pavement temperature and is a special case of solving the differential equation (4) [9]. Using this equation, initial conditions were defined in the form of vertical temperature profiles in the road pavement structure, Figure. 2.

$$\vartheta(x, t) = \vartheta_M + \Delta A_\vartheta \cdot e^{-\zeta} \cdot \cos(\psi \cdot t - \zeta) \quad (7)$$

where:

$$\zeta = x \cdot \sqrt{\frac{\pi}{a \cdot t_p}}$$

$$\psi = \frac{2 \cdot \pi}{t_p}$$

$$a = \frac{\lambda_w}{\rho \cdot c_p}$$

$\vartheta(x, t)$  – temperature at depth x of the structure, and at time t,

$\vartheta_M$  – average surface temperature of the asphalt pavement,

$\Delta A_\vartheta$  – amplitude of temperature period on the surface of the pavement,

$t_p$  – time period.

This equation shows that the change in temperature on the pavement surface causes a change in the temperature inside the surface layers. The speed at which this happens depends on the heat transfer capacity of the material as well as on the temperature difference between layers. Figure 1 shows the temperature variability as a function of time for different depths in the pavement structure. Figure 2 shows temperature profiles at the depth of the pavement and soil, depending on the amplitude and time period.

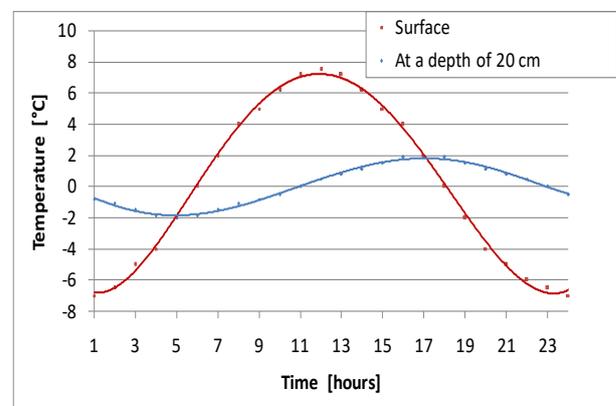
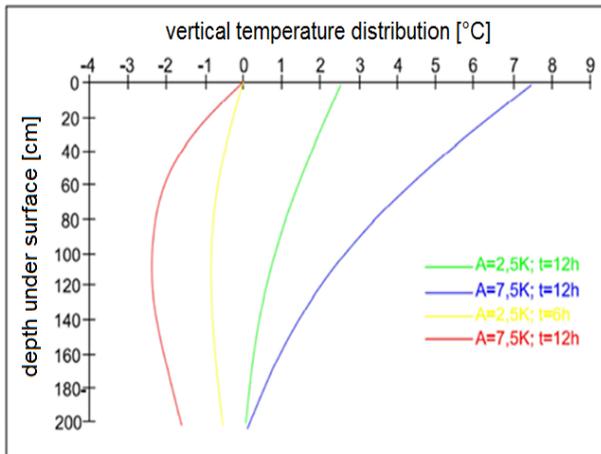


Fig. 1. Temperature variability on the pavement surface and at a depth of 20 cm per day (based on [9]).



**Fig. 2.** Temperature profiles at depth under the surface of pavement (based on [9])

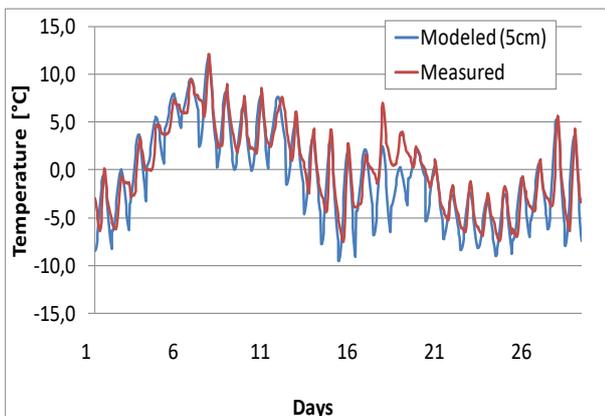
Analyzing the parameters of the equation (7) and the obtained graphs it can be stated that the temperature changes depend on the following parameters:

- temperature amplitudes for periods,
- length of time intervals,
- physical and thermodynamic properties of materials.

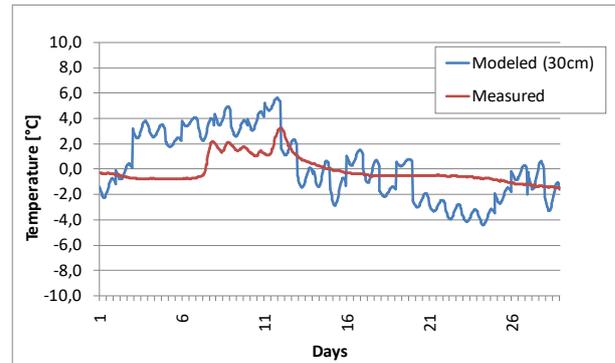
From the scientific and engineering point of view, it is important to test and analyze the thermal parameters of materials used for the construction of road pavement. The accuracy of determining their value will affect the precision of the results of analyzes carried out using theoretical models.

## 4 Results and discussion

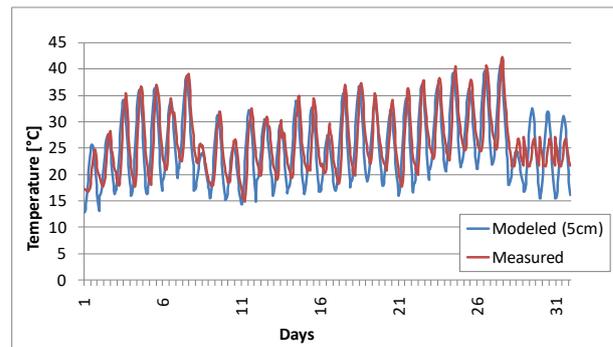
The results obtained from transient thermal analysis are compared to those obtained from field measurements. The analyzes of monthly temperature variability in February and August are presented. In addition, the results of daily temperature variability on February 15 and August 27. The results of thermal analyzes are shown in Figures 3-6.



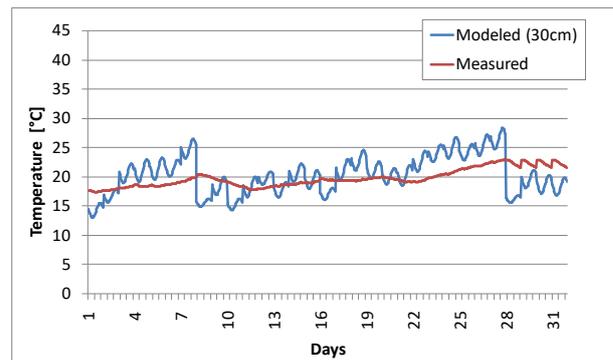
**Fig. 3.** Comparison of the monthly temperature variability in February obtained from the model and measurements at a depth of 5cm



**Fig. 4.** Comparison of the monthly temperature variability in February obtained from the model and measurements at a depth of 30cm



**Fig. 5.** Comparison of the monthly temperature variability in August obtained from the model and measurements at a depth of 5cm



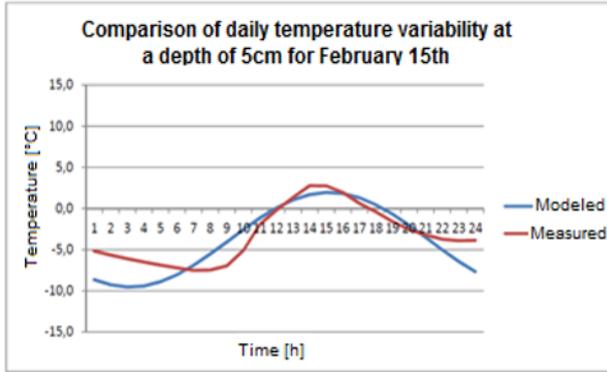
**Fig. 6.** Comparison of the monthly temperature variability in August obtained from the model and measurements at a depth of 30 cm

A comparison of the results at a depth of 5 cm indicates that the results from the model well represent temperature changes. Both the temperature amplitudes and the temperature cycles themselves are similar to reality.

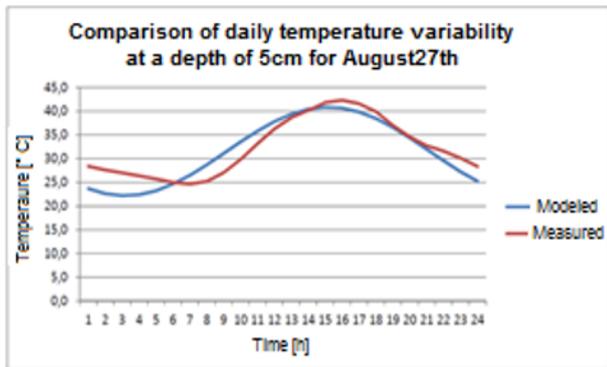
At a depth of 30cm, the model shows less variation than in the case of 5cm, so the depth effect is taken into account. However, the measurements indicate that the temperature is much more stable than the model shows. The model has abrupt temperature changes. This is due to the fact that average temperatures on the surface of the pavement in the following days and their amplitudes are different. Temperatures obtained from the model deviate

to a certain extent from those measured, however the differences do not exceed about 5 °C.

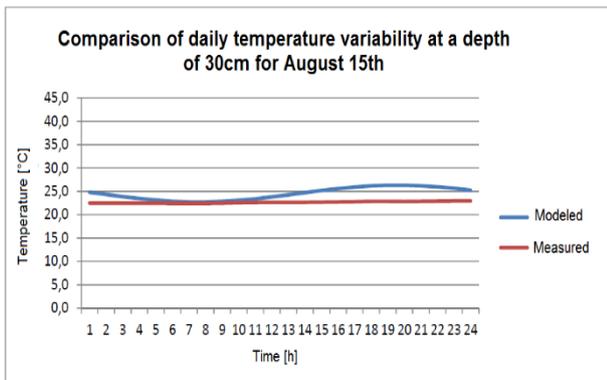
Comparisons of the daily temperature variability obtained from the model and measured for February 15, August 27 and August 15 at a depth of 5 cm and 30 cm are shown in Figures 7-9.



**Fig. 7.** Comparison of daily temperature variability for temperatures obtained from the model and measurements at a depth of 5cm for February 15th



**Fig. 8.** Comparison of daily temperature variability for temperatures obtained from the model and measurements at a depth of 5cm for August 27th

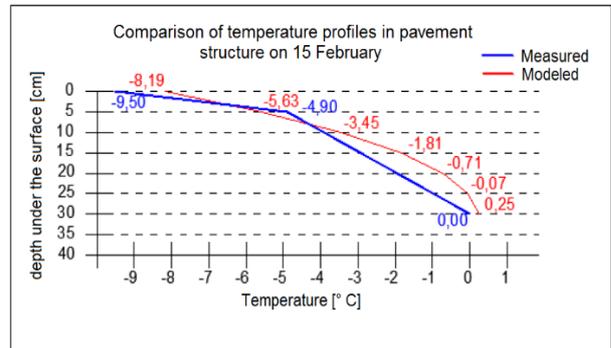


**Fig.9.** Comparison of daily temperature variability for temperatures obtained from the model and measurements at a depth of 30cm for August 15th

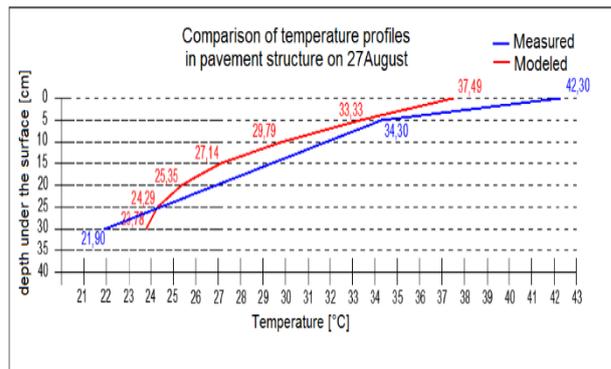
Comparison of daily variability indicates that the results from the model represent well the results of field measurements for both the depth of 5 cm and 30 cm. One can see that at a depth of 30 cm the temperature amplitude is small. The influence of periodicity of model function is

also visible. For a depth of 5cm, the amplitude is much higher, which is confirmed by measurements.

Comparisons of the temperature profiles in the pavement structure for a given day of February and August are shown in Figure 10 and Figure 11.



**Fig.10.** Comparison of temperature profiles in pavement structure for 00.00 on 15 February.



**Fig.11.** Comparison of temperature profiles in pavement structure for 12.00 on 27 August.

The temperature distribution in the pavement structure indicates that the model well defines the temperature for the constant time and the variable depth. Thanks to the fact that in the model it was possible to obtain data for any depth, it was possible to specify the temperature profile more accurately than in the case of measured values. For points in which the temperature was measured, the difference between the values measured and received from the model is small. In the case of analysis in the month of February it is less than 1 °C. In August, temperature differences within the structure are slightly higher than in February. However, it can be assumed that the model essentially correctly determines the temperature distribution within the pavement structure.

The following factors influence the temperature distribution in the road pavement significantly: surface temperature of the pavement, as a result of temperature convection, radiation and conduction, thickness of pavement structure layers, value of conductivity of building materials used in pavement, values of thermal conductivity of the native soil.

Differences in measured and calculated temperature may be caused by inappropriate temperature of natural soil. It is a boundary condition for thermal analyzes. In addition, the inaccuracy of results can also be influenced by the lack of data on the actual state of compaction and

moisture of the pavement and soil layers. Material constants characterizing thermal properties of individual layers were adopted from the literature [9, 14, 15, 16]. Types and thickness of layers based on technical documentation and construction design of the analyzed road section.

## 5 Conclusions

This article deals with problems related to the heat transfer in asphalt pavement. The main goal was to compare the temperature distributions in the selected road pavement structure based on empirical data and the theoretical model. The analyzes were carried out for the selected road section located on the A4 motorway.

In order to properly take into account the influence of thermal conditions on the behavior of the pavement structure, it is necessary to know these conditions in a given area. A good method to determine climatic conditions is to use the results of meteorological measurements. However, it is a relatively expensive, requiring specialized equipment and long observation time (many years). In order to predict the behavior of newly designed pavement structures, it is therefore necessary to apply modeling, e.g. using the Fourier-Kirchhoff heat transfer equation (3).

Of course, it is also necessary to know the thermal properties of materials used for pavement structure, such as specific heat, thermal conductivity as well as boundary and initial conditions. The comparisons carried out in this work show that the use of ready-made models is possible, but it requires calibration. These models represent well the profile and temperature variability at different depths of the pavement structure. However, it is characteristic to lower or overestimate the instantaneous values in relation to the results obtained from field measurements.

The analyzes carried out allowed to formulate the following conclusions:

- in the road pavements there are three types of thermal processes (thermal convection, thermal radiation, thermal conduction). This leads to changes in the temperature distribution in the structure both in the daily and annual periods. Physical model describing the phenomenon of convection and radiation, allowing to determine the temperature of the wearing layer of pavement structure, not taking into account the thermal properties of the structure itself. With certain assumptions, it is possible to determine the temperature of the wearing layer of the asphalt pavement, which can be treated as a boundary condition for further analysis,
- the used heat flow model well shows the real heat transfer in the road pavement. It is possible to distinguish the time of day and night, which is characterized by the opposite return of the heat flux vector - the transport of thermal energy in the direction of the surrounding - the pavement. One can also observe a decrease in temperature with the pavement structure depth and the phase shift between the graphs. It is related to the thermal inertia

phenomenon and requires calibration to local conditions.

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