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Modeling of transient temperature distribution in multilayer asphalt pavement

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Abstract. Mathematical model has been developed for determination of temperature field in multilayer pavement and subgrade, which considers transfer of heat by conduction and convection, receiving of heat from total solar radiation and atmosphere emission, output of heat due to the emission from the surface of pavement. The developed model has been realized by the finite element method for two dimensional problem using two dimensional second order finite element. Calculations for temperature field have been made with the programme realized on the standard mathematical package MATLAB. Accuracy of the developed model has been evaluated by comparison of temperatures, obtained theoretically and experimentally. The results of comparison showed high accuracy of the model. Long-term calculation (within three months) has been made in pavement points in accordance with the data of meteorological station for air temperature. Some regularities have been determined for variation of temperature field.

Keywords: asphalt pavement; finite element method; transient temperature distribution

1. Introduction

Asphalt is one of the widely used road materials in the world. It is known that strength and deformation properties of the asphalt depend greatly upon temperature (Yoder and Witczak 1975, Papagiannakis and Masad 2008, MS-4 2007). On the stage of pavement design one should have reliable data for distribution and variation of temperature in hot mix asphalt layers (Huang 2004, AASHTO MEPDG-1 2008). For this purpose mathematical model should be developed, which allows prediction of non-stationary temperature field in pavement and subgrade depending on climatic and weather conditions. Primary energy source, reaching the surface of the earth (surface of pavement), is the Sun (Geiger 1959). Energy of the Sun reaches the surface of pavement as a kind of shortwave direct solar radiation and shortwave scattered solar energy (Anderson 1983). Pavement, having absorbed solar radiation, starts emitting long-wave emission back into the atmosphere. There is a convective heat transfer between atmosphere and pavement surface. Also there is a continuous heat transfer through conduction in pavement and subgrade (Carslow and Jaeger 1959, Dewitt and Incropera 1996, Ozisik 1985). The developed model should consider all the above mentioned types of heat transfer, connected with pavement structure.

The developed model should be realized in computer programming, which allows making

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calculations with high speed to obtain numerous calculation that simulate temperature distribution in twenty years. It is also desirable for the chosen computer programming to allow realization of model as simple as possible. Perhaps, to achieve the above requirements it is sufficient to realize model in modern fast operating mathematical package, such as MATLAB and MATHCAD.

One of the first researchers, who tried to connect temperature of pavement with weather parameters, was Barber (1957). He, reviewing multilayer pavement as one layer, obtained simple analytical equation, connecting maximum temperature of pavement surface with wind speed, air temperature and solar radiation. Solaimanian and Kennedy (1993) proposed formula describing dependence of maximum pavement temperature on air temperature, short wave and long-wave solar radiation. This formula also considered convective heat transfer between pavement surface and environmental air. Analytical dependencies, proposed by Barber, Solaimanian and Kennedy, have the following essential disadvantages. Firstly, they are intended for prediction of the maximum temperature of pavement surface, i.e., they are not able to describe temperature variation during a day and longer periods; also they are not able to give values of temperature in other points of pavement, except for its surface. Secondly, they do not consider multilayer condition for pavement structure and subgrade, difference in their geometrical, physical and thermal characteristics.

The article of Shao *et al*. (1994) uses analytical solution for determination of temperature field in pavement, obtained in the work of Carslow and Jaeger (1959). However, it also obtained for one-dimensional semi-infinite body.

The work (Wang *et al*. 2009) shows modified model based on analytical approach. It considered convective heat exchange, daily variety of air temperature and solar radiation, as well as multilayer structure for pavement and subgrade. However, the disadvantage of this model is the accepted assumption that the temperature varies in radial direction on exponential dependence. Distribution of temperature can substantially differ from the accepted one in some real conditions.

The works of Hermanson (2000, 2004) show equations included in to the main formula for determination of maximum temperature for pavement surface, obtained in the work of Solaimanian and Kennedy (1993) and they say that finite-difference method models heat conductivity in pavement and subgrade.

There are some well-known works, which contain finite element method. To determine non-stationary temperature field for pavement Shibib *et al*. (2012), Mallick *et al*. (2014) and Minhoto *et al*. (2005) used one dimensional, two dimensional (triangle) and three dimensional (parallelepiped) finite elements respectively. All these finite elements relate to the group of linear elements, within which temperature varies under linear dependence. To increase accuracy for calculations in finite element method one can use elements of higher order, for example, finite elements of the second order (Zienkiewicz *et al*. 2013, Segerlind 1976).

Diefenderfer *et al*. (2003, 2006) determined correlation dependence between maximum daily temperature for pavement and maximum daily temperature for air, daily solar radiation, depth of the point for pavement. They fixed this dependence based on data, obtained from road sections, located in Virginia, USA. It is known that such empirical dependencies give low accuracy in other climatic conditions.

Development of mathematical model, describing temperature field in pavement structure and subgrade soil of the highway, considering their physical and thermal characteristics and external factors, is a complicated task. Perhaps, that is why, practically till date, some researchers use simple and inaccurate correlation dependencies. For example, Choi *et al*. (2011) describe temperature profile of pavement by simple power dependence on the depth; Matic *et al*. (2012)

represent maximum and minimum temperature of pavement as functions only of maximum and minimum daily air temperature. However, some researchers prefer to measure temperature of pavement directly. For example, Islam and Tarefder (2013), when investigating stress and deformation in pavement, measured temperature with the help of special temperature sensors.

In this work mathematical model has been developed for determination of non-stationary temperature field in multilayer pavement and subgrade. The model considers receipt of thermal energy into pavement at the expense of total solar radiation and atmosphere emission, energy outflow at the expense of long-wave radiation into atmosphere, convective heat transfer between the atmosphere and pavement surface and conductive transfer of heat in pavement and subgrade. The model is realized by the finite element method for the problem of two-dimensional heat transfer in the standard mathematical MATLAB package using finite elements of second order with eight nodes. Accuracy of the developed model is checked by comparison of temperatures received by calculation and experiment. Prediction of temperature variety is carried out by means of model in characteristic points of pavement.

2. Heat balance on the pavement surface

Based on the theory of heat conductivity (Carslow and Jaeger 1959, Dewitt and Incropera 1996, Ozisik 1985), the heat balance on the pavement surface can be presented as follows (Fig. 1)

$$q_k + q_c + q_s + q_a + q_e = 0 \tag{1}$$

where, q_k is energy transferred by conduction, q_c is energy transferred by convection, q_s is energy obtained at the expense of total solar radiation, q_a is energy obtained by atmosphere emission and q_e is energy of the earth surface emission.

2.1 Conductive heat transfer

The equation of non-stationary heat conductivity obtained on the basis of the Fourier's law, and

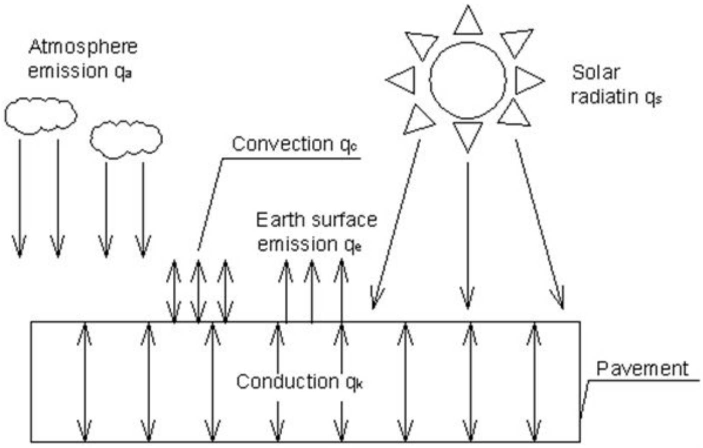


Fig. 1 Schematic view of heat balance on the pavement surface

describing process of conductive heat transfer in a solid body, represents the second order differential equation of the parabolic type (Dewitt and Incropera 1996, Ozisik 1985)

$$K_x \frac{\partial^2 T}{\partial x^2} + K_y \frac{\partial^2 T}{\partial y^2} = \rho c \frac{\partial T}{\partial t} \tag{2}$$

where, K_x, K_y are heat conductivity coefficients in the directions of axes of coordinates x and y respectively, W/(m·°C), T is temperature, °C, ρ is density, kg/m^3 and c is specific heat capacity, W·s/(kg·°C).

2.2 Convective heat transfer

Convective heat transfer occurs between the surface of pavement and ambient air. The heat flow with convective heat transfer is determined by Eq. (3)

$$q_c = h_c (T_0 - T_{air}) \tag{3}$$

where, h_c is convective heat transfer coefficient, W/(m^2·°K), T_0 is temperature of pavement surface, °K and T_{air} is air temperature, °K.

The work (Hermanson 2000) gives formula for determination of convective heat transfer between pavement and ambient air

$$h_c = 698.24 \cdot \left[0.00144 \cdot T_{av}^{0.3} \cdot U^{0.7} + 0.00097 \cdot (T_0 - T_{air})^{0.3}\right] \tag{4}$$

where, U is wind speed, m/s and T_{av} is average temperature for pavement surface and air calculated as

$$T_{av} = (T_0 + T_{air})/2 \tag{5}$$

2.3 Heat flow of total solar radiation

Heat flow from total solar radiation, received by pavement surface, is calculated by Eq. (6) (Diefenderfer *et al*. 2006)

$$q_r = I_0 \cdot k_r \cdot E_0 \cdot \cos(\varphi + \delta) \cdot k_h \tag{6}$$

where, I_0 is the solar constant equal to 1370 W/m^2. k_r is coefficient considering reflection of solar radiation into outer space, E_0 is coefficient considering eccentricity of the Earth orbit, φ is geographical latitude of area, grades, δ is angle of declination of the Sun, grades and k_h is coefficient considering change of receipt of the solar radiation during the light day.

Coefficient, considering eccentricity of the Earth orbit (Velasquez *et al*. 2008), is determined by Eq. (7)

$$E_0 = 1.000110 + 0.034221 * \cos(\mathrm{G}) + 0.001280 * \sin \mathrm{G} + 0.000719 * \cos 2\mathrm{G} + 0.000077 * \sin 2\mathrm{G} \tag{7}$$

where, parameter G is calculated by Eq. (8) (Diefenderfer *et al*. 2006)

$$G = \frac{2\pi d}{365} \tag{8}$$

Here d is serial number of days in a year, since January 1.
Angle of declination of the Sun can be obtained from Eq. (9) (Diefenderfer *et al*. 2006)

$$\begin{aligned}\delta = (&0.006918 - 0.39992\cos G + 0.070257\sin G - 0.006758\cos 2G \\ &+ 0.000907\sin 2G - 0.002697\cos 3G + 0.00148\sin 3G)\times\left(\frac{180}{\pi}\right)\end{aligned} \tag{9}$$

Coefficient k_h is calculated by Eq. (10)

$$k_h = \frac{\sin\left(t - \frac{\pi}{2}\right) + 1}{2} \tag{10}$$

where, t is current time, which changes from the moment of sunrise t_{sr} to the moment of sunset t_{ss}.

2.4 Heat flow from atmosphere emission

The atmosphere absorbs solar radiation and emits long-wave radiation in the direction of the Earth surface. Heat flow from this radiation is calculated under the Stefan-Boltzman's law

$$q_a = \varepsilon_a \cdot \sigma \cdot T_{air}^4 \tag{11}$$

where, ε_a is coefficient of absorption of pavement surface, σ is the Stefan-Boltzman's constant equal to $\sigma = 5{,}67 \cdot 10^{-8}$ W/(m$^2\cdot{}^\circ$K^4) and T_{air} is air temperature, °K.

2.5 Heat flow of the earth emission

Earth surface, absorbing an arriving solar radiation, is heated, and as the black body itself emits long-wave radiation into atmosphere. Heat flow, formed on the basis of such radiation, is also calculated under the Stefan-Boltzman's law

$$q_e = \varepsilon_e \cdot \sigma \cdot T_0^4 \tag{12}$$

where, ε_e is emission coefficient, σ is the Stefan-Boltzman's constant and T_0 is pavement surface temperature, °K.

Considering dependencies (2), (3), (6), (11) and (12), equation of heat balance on the pavement surface can be represented as follows

$$K_x \frac{\partial^2 T}{\partial x^2} + K_y \frac{\partial^2 T}{\partial y^2} - \rho c \frac{\partial T}{\partial t} + h_c(T_0 - T_{air}) + I_0 k_r E_0 \cos(\varphi + \delta) k_h + \varepsilon_a \sigma T_{air}^4 - \varepsilon_b \sigma T_0^4 = 0 \tag{13}$$

3. Finite element model

Eq. (13) shows condition of heat balance on pavement surface. It can be changed for pavement and subgrade as follows

$$K_x \frac{\partial^2 T}{\partial x^2} + K_y \frac{\partial^2 T}{\partial y^2} = \rho c \frac{\partial T}{\partial t} \tag{14}$$

with boundary conditions

$$K_x \frac{\partial T}{\partial x} l_x + K_y \frac{\partial T}{\partial y} l_y + h_c (T_0 - T_{air}) + q = 0 \tag{15}$$

where, l_x, l_y are directing cosines.

In Eq. (15) heat flow q is calculated by Eq. (16)

$$q = I_0 k_r E_0 \cos(\varphi + \delta) k_h + \varepsilon_a \sigma T_{air}^4 - \varepsilon_b \sigma T_0^4 \tag{16}$$

It is known that finite-element analog of differential Eq. (14) with boundary conditions (15) can be obtained by minimization of the following functional (Segerlind 1976, Zienkiewicz *et al.* 2013)

$$\chi = \int_V \frac{1}{2} \left[K_x \left(\frac{\partial T}{\partial x} \right)^2 + K_y \left(\frac{\partial T}{\partial y} \right)^2 - 2\rho c \frac{\partial T}{\partial t} T \right] dV + \int_{S_q} qTds + \int_{S_c} \frac{h_c}{2} \left(T^2 - 2TT_{air} + T_{air}^2 \right) \tag{17}$$

where, V is volume of finite element, m^3, S_q is area of a side of finite element, for which heat flow q is set under Eq. (16), m^2 and S_c is area of a side of finite element, for which heat flow is set based on convection and calculated by Eq. (3), m^2.

Functional (17) represents by itself the amount of heat, accumulated by it at the moment of stationary temperature condition. One can see that it also includes in itself boundary conditions (15).

After minimization of functional (17) for all finite elements the finite-element analog of differential Eq. (14) will be

$$[C] \frac{\partial T}{\partial t} + [K]\{T\} + \{Q\} = 0 \tag{18}$$

where, $[C]$ is heat inertia matrix of the finite element system, $[K]$ is heat conductivity matrix of the system, $\{T\}$ is nodal temperature vector in the system and $\{Q\}$ is vector of heat flows in the system.

Inputs of each finite element into matrixes $[C]$, $[K]$ and $\{Q\}$ are expressed by Eqs. (19)-(21)

$$\left[c^e \right] = \int_V \rho c \left[N^e \right]^T \left[N^e \right] dV \tag{19}$$

$$\left[k^e \right] = \int_V \left[B^e \right]^T \left[D^e \right] \left[B^e \right] dV + \int_{S_c} h_c \left[N^e \right] \left[N^e \right] ds \tag{20}$$

$$\{q^e\} = \int_{S_q} q\left[N^e\right]^T ds - \int_{S_c} h_c T_{air}\left[N^e\right]^T ds \tag{21}$$

where, $[c^e]$ is heat inertia matrix of a finite element, $[k^e]$ is heat conductivity matrix of a finite element, $\{q^e\}$ is vector of heat flows of a finite element and $[N^e]$ is shape functions vector of a finite element.

In Eq. (20) matrix of conductivity for finite element $[D^e]$ consists of conductivity coefficients

$$\left[D^e\right] = \begin{bmatrix} k_x & 0 \\ 0 & k_y \end{bmatrix} \tag{22}$$

Matrix $[B^e]$ consists of partial derivatives from shape functions of finite element for global coordinates x and y

$$\left[B^e\right] = \begin{bmatrix} \dfrac{\partial N_1}{\partial x} & \dfrac{\partial N_2}{\partial x} & \cdots & \dfrac{\partial N_8}{\partial x} \\ \dfrac{\partial N_1}{\partial y} & \dfrac{\partial N_2}{\partial y} & \cdots & \dfrac{\partial N_8}{\partial y} \end{bmatrix} \tag{23}$$

In this work the research area was discretized for second order finite elements with 8 nodes (Segerlind 1976, Zienkiewicz *et al*. 2013). Shape functions of such finite element, i.e. components of the vector $[N^e]$, are as follows

$$\begin{aligned} N_1 &= -\frac{1}{4}(1-\xi)(1-\eta)(\xi+\eta+1) \\ N_2 &= \frac{1}{2}\left(1-\xi^2\right)(1-\eta) \\ N_3 &= \frac{1}{4}(1+\xi)(1-\eta)(\xi-\eta-1) \\ N_4 &= \frac{1}{2}\left(1-\eta^2\right)(1+\xi) \\ N_5 &= \frac{1}{4}(1+\xi)(1+\eta)(\xi+\eta-1) \\ N_6 &= \frac{1}{2}\left(1-\xi^2\right)(1+\eta) \\ N_7 &= -\frac{1}{4}(1-\xi)(1+\eta)(\xi-\eta+1) \\ N_8 &= \frac{1}{2}\left(1-\eta^2\right)(1-\xi) \end{aligned} \tag{24}$$

In Eq. (24), ξ and η represent by themselves horizontal and vertical coordinates of finite element points in local coordinate system $\xi 0\eta$.

Derivatives $\frac{\partial N_1}{\partial x}, \frac{\partial N_2}{\partial x}, \dots, \frac{\partial N_8}{\partial x}, \frac{\partial N_1}{\partial y}, \frac{\partial N_2}{\partial y}, \dots, \frac{\partial N_8}{\partial y}$ are determined on the known dependency (Segerlind 1976, Zienkiewicz *et al*. 2013)

$$\begin{Bmatrix} \dfrac{\partial N_i}{\partial x} \\ \dfrac{\partial N_i}{\partial y} \end{Bmatrix} = [J]^{-1} \begin{Bmatrix} \dfrac{\partial N_i}{\partial \xi} \\ \dfrac{\partial N_i}{\partial \eta} \end{Bmatrix}, \quad i = 1, 2, ..., 8 \tag{25}$$

In the dependency (25), $[J]^{-1}$ represents by itself the matrix inverse to Jacobian $[J]$. Jacobian matrix in this case is as follows

$$[J] = \begin{bmatrix} \dfrac{\partial x}{\partial \xi} & \dfrac{\partial y}{\partial \xi} \\ \dfrac{\partial x}{\partial \eta} & \dfrac{\partial y}{\partial \eta} \end{bmatrix} \tag{26}$$

Matrixes $[c^e]$, $[k^e]$ and vector $\{q^e\}$ of finite element are determined by numerical integration in local coordinate system. Transition from global coordinate system $x0y$ to local coordinate system $\xi 0\eta$ is realized through replacement of integrating variables

$$\begin{aligned} dV &= \left|\det[J]\right| r d\xi d\eta \\ ds &= \left|\det[J]\right| r d\xi \end{aligned} \tag{27}$$

where, r is thickness of finite element, equal in our case to 1.

Then integral in Eqs. (19)-(21) are written as follows

$$\int_V [B^e]^T [D^e][B^e] dV = \int_{-1}^{1}\int_{-1}^{1} [B^e]^T [D^e][B^e] \left|\det[J]\right| d\eta d\xi \tag{28}$$

$$\int_V \rho c [N^e]^T [N^e] dV = \rho c \int_{-1}^{1}\int_{-1}^{1} [N^e]^T [N^e] \left|\det[J]\right| d\eta d\xi \tag{29}$$

$$\int_{S^e} h_c [N^e]^T [N^e] dS = h_c \int_{-1}^{1} [N^e]^T [N^e] \left|\det[J]\right| d\xi \tag{30}$$

$$\int_{S^e} h_c T_{air} [N^e]^T \, dS = h_c T_{air} \int_{-1}^{1} [N^e]^T \left|\det[J]\right| d\xi \tag{31}$$

$$\int_{S^q} q [N^e]^T \, dS = q \int_{-1}^{1} [N^e]^T \left|\det[J]\right| d\xi \tag{32}$$

Numerical integration in Eqs. (28)-(32) has been carried out with help of Gauss-Legendre's quadrature formula. In this case formulas of numerical integration are as follows

$$\int_{-1}^{1}\int_{-1}^{1} f_1(\xi,\eta)\, d\eta d\xi = \sum_{i=1}^{n}\sum_{j=1}^{n} H_i H_j f_1(\xi_i,\eta_j) \tag{33}$$

$$\int_{-1}^{1} f_2(\xi)\, d\xi = \sum_{i=1}^{n} H_i f_2(\xi_i) \tag{34}$$

where, f_1 (ξ, η) are integrand functions in Eqs. (28)-(29), f_2 (ξ) are integrand functions in Eqs. (30)-(32), H_i, H_j are weight coefficients, ξ_i, η_i are coordinates of integration points in local system of coordinates and n is the number of points in the directions of coordinate axes ξ and η, which in our case is equal to 2.

To have values of temperature in points of the researched area, it is necessary to solve the linear differential Eq. (18) in each time point t. For this purpose we will replace a derivative $\frac{\partial T}{\partial t}$ in the equation with its finite difference analog

$$\frac{\partial T}{\partial t} = \frac{1}{\Delta t}\left[\{T\}_1 - \{T\}_0\right] \tag{35}$$

where, $\{T\}_0$, $\{T\}_1$ are vectors of temperature at instant times t_0 and t_1 respectively and Δt is interval of time between instant times t_0 and t_1, i.e., $\Delta t = t_1 - t_0$.

Difference Eq. (35) has been written for mean point of interval of time Δt. Vectors $\{T\}$ and $\{Q\}$ should be also calculated for the same mean point of interval of time

$$\{T\}^* = \frac{1}{2}\left[\{T\}_0 + \{T\}_1\right] \tag{36}$$

$$\{Q\}^* = \frac{1}{2}\left[\{Q\}_0 + \{Q\}_1\right] \tag{37}$$

Having substituted Eqs. (35)-(37) into Eq. (18), we will have

$$\left(\frac{2}{\Delta t}[C] + [K]\right)\{T\}_{t+\Delta t} = \left(\frac{2}{\Delta t}[C] - [K]\right)\{T\}_t - \{Q\}_{\Delta t} \tag{38}$$

where, $\{T\}_t$, $\{T\}_{t+\Delta t}$ are vectors of temperature at instant times t and $t + \Delta t$ respectively and $\{Q\}_{\Delta t}$ is vector of heat flow in system, accumulated at the interval of time Δt.

Eq. (38) represents by itself finite element solution of the problem for non-stationary heat transfer. Procedure of its realization is efficient, because matrixes $[C]$ and $[K]$ are formed only once, and for each interval of time only vector of heat flow $\{Q\}_{\Delta t}$ is calculated.

The area of research is accepted in the form of the rectangle consisting of horizontal layers. Boundary conditions are set as follows: on lateral vertical borders (Fig. 2, lines AC and BD) there is no transfer of heat flows; on the lower bound (Fig. 2, line CD) the values of temperature are

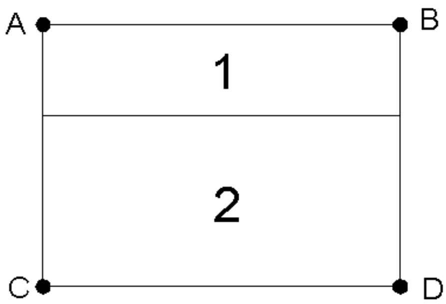


Fig. 2 Schematic view of the research area: (1) multilayer pavement; (2) subgrade

considered as known and are set from experimental data.

4. Comparison of experimental and calculated temperatures

4.1 Experiment

For the purpose of obtaining information for temperature variation in points of pavement and subgrade on the site which is near to Turkestan city (South Kazakhstan Region) temperature sensors were installed in the highway "Kyzylorda-Shymkent" in 2013. Sensors are located in 11 points of pavement and subgrade, lying on one vertical. The deepest point of sensors location is 2.40 m from hot mix asphalt pavement surface. The road section has 4 lanes, each of which has width of 3.5 m. Construction of the road was completed in 2013.

The pavement structure on a trial section includes: stone mastic asphalt concrete – 0.05 m; porous asphalt concrete – 0.10 m; high-porous asphalt concrete – 0.13 m and sand and gravel mix – 0.40 m. Subgrade consists of dusty sand.

4.2 Calculation

The model of non-stationary heat transfer in a pavement structure, described in Sections 2 and 3 of this article, was realized on a mathematical MATLAB package. For check of adequacy for the developed model, the values of temperature received with its help in characteristic points of pavement, were compared to similar experimental data. For comparison of calculation and experimental temperatures, two periods of time were chosen: from July 25 to July 31 and from October 23 to October 29, 2013. Figs. 3-4 show diagrams of air temperature variations obtained from data of meteorological station and temperature of hot mix asphalt pavement surface received by calculations for the chosen periods. The first period is characterized by hot weather. Air temperature reaches to 44°C in a shadow, and the hot mix asphalt pavement surface is heated up to 60°C. At night air temperature and temperature of hot mix asphalt pavement surface reduce to 20°C and 26°C respectively. With daily air temperature variation for 24°C temperature of hot mix asphalt pavement surface changes for 34°C. It is necessary to notice that during the whole chosen summer period temperature of hot mix asphalt pavement surface is always higher than air temperature. The difference of air temperatures at night is 6-12°C, and in the afternoon – 12-20°C. The second chosen period of time corresponds to an autumn season. During this period the maximum air temperature rises only to 18°C, and the surface of hot mix asphalt pavement is heated up to 29°C. In separate days air temperature and temperature for surface of hot mix asphalt pavement falls to 0°C. Temperature for surface of hot mix asphalt pavement is higher than air temperature at the average for 4-13°C in the afternoon and for 1-4°C at night. Besides, in the middle of this period continuous air temperature drop occurs, which is typical to autumn season of the year. Necessary characteristics of pavement layers materials and subgrade soil for carrying out calculations are shown in Table 1.

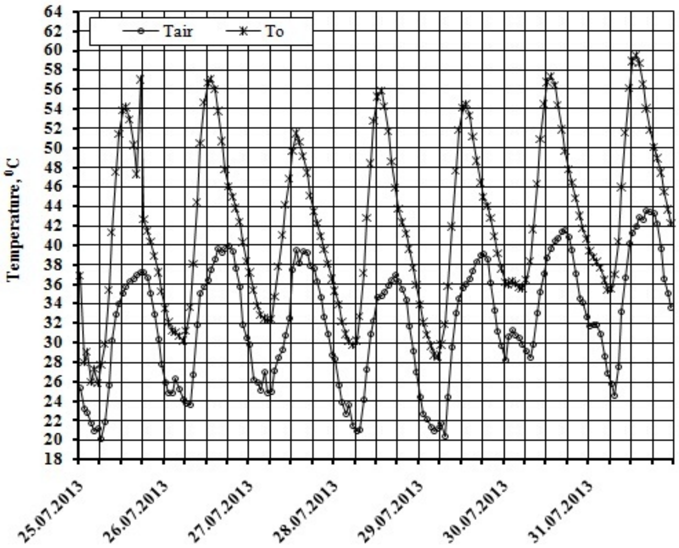


Fig. 3 Air temperature (T_{air}) and asphalt pavement surface temperature (T_0) in the chosen summer period

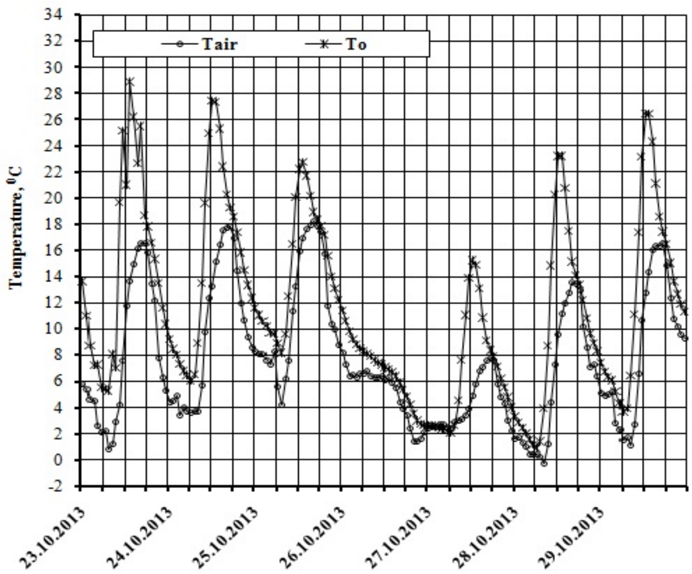


Fig. 4 Air temperature (T_{air}) and asphalt pavement surface temperature (T_0) in the chosen autumn period

Table 1 Characteristics of materials for pavement layers and subgrade soil

Material, soil	Thickness, cm	Density, t/m^3	Heat conductivity coefficient, W/(m^2·°C)	Heat capacity, W·s/(kg·°C)
Stone mastic asphalt	5	2400	1,40	850
Coarse-grained porous asphalt concrete	10	2300	1,25	850
Coarse-grained high porous asphalt concrete	13	2200	1,10	850
Sand and gravel mix	40	1875	1,89	975
Dusty sand	172	1850	1,91	1100

The research area in the form of rectangle had the following sizes: width is 3.0 m; height is 2.4 m. It was discretized on 420 plane quadrangular second order finite elements. Values of temperature on the lower bound area were based on experimental data and changed within 26.8°C and 27.4°C from July 25 to July 31 and within 23.7°C and 22.8°C from October 23 to October 29, 2013.

When determining a convective heat flow the calculated value of wind speed was accepted as equal to 3.2 m/s in July and 2.5 m/s in October for the considered location according to the standard (SNIP 2005).

When calculating heat flow from total solar radiation the coefficient value κ_r varied within 0.50-0.85 in July and within 0.21-0.44 in October taking into account weather conditions on the area. Geographic latitude of the area α = 43°15′. For the chosen area according to meteorological researches (Abdullina 1989) time of sunrise (t_{sr}) and sunset (t_{ss}) in last decade of July were

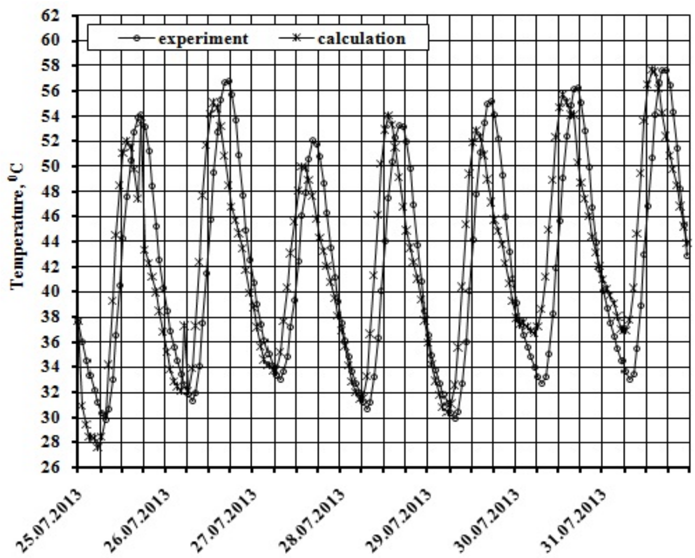


Fig. 5 Temperature of asphalt concrete layer in the depth of 0.02 m in summer period

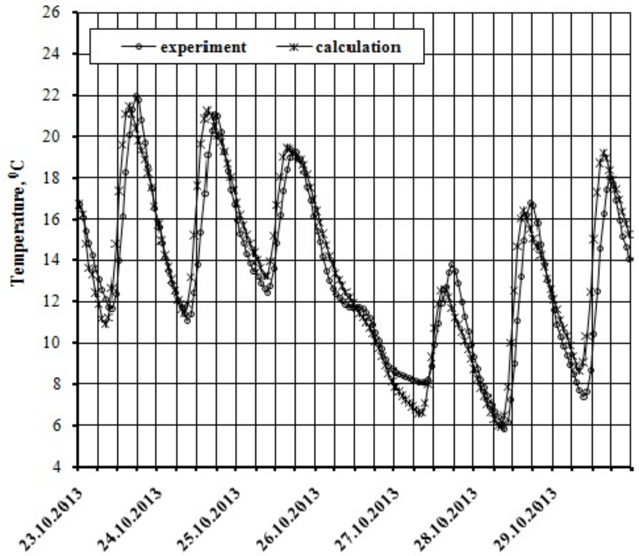


Fig. 6 Temperature of asphalt concrete layer in the depth of 0.10 m during autumn period

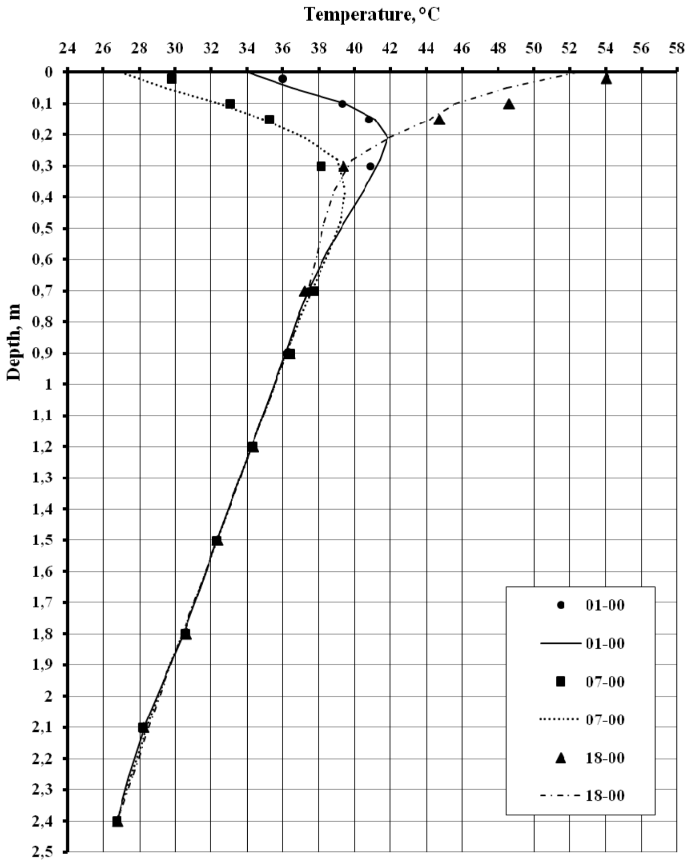


Fig. 7 Distribution of temperature in points of pavement and subgrade on July 25, 2013

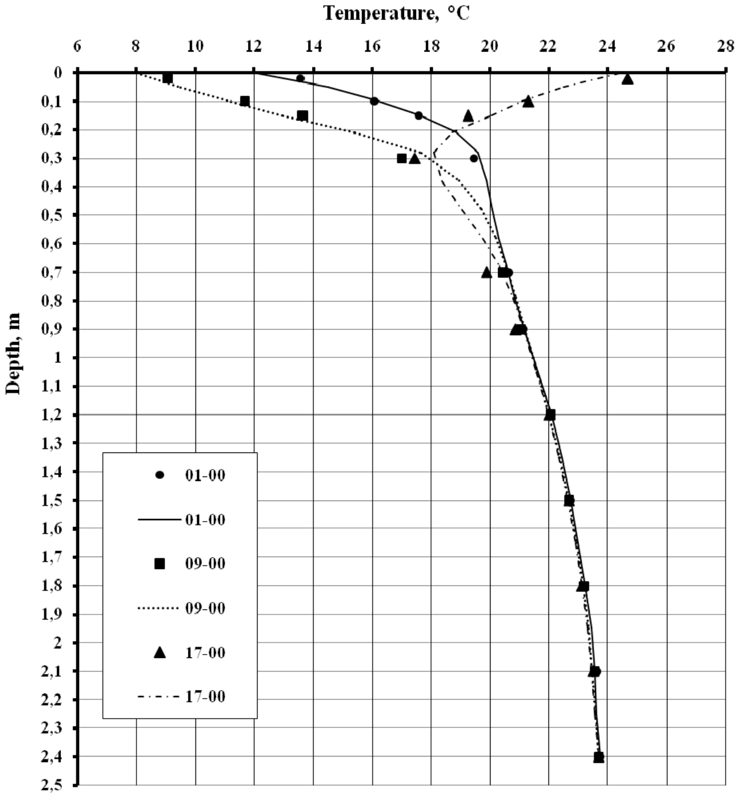


Fig. 8 Distribution of temperature in points of pavement and subgrade on October 23, 2013

accepted as equal to t_{sr} = 4 hours 50 minutes and t_{ss} = 19 hours 10 minutes, and in October t_{sr} = 6 hours 50 minutes and t_{ss} = 17 hours 10 minutes.

Coefficient of heat emission from the atmosphere ε_a = 0.55. The coefficient of heat emission from pavement surface ε_a can change within 0.85 and 0.93. In our calculations its average value is accepted as equal to 0.9.

4.3 Comparison

Fig. 5 shows diagrams for temperature variations in the point of asphalt concrete layer located at the depth of 0.02 m in the chosen summer period. Similar diagrams for the point of asphalt concrete layer located at the depth of 0.10 m in the chosen autumn period are given in the Fig. 6. Apparently, coincidence of the calculated values of temperatures with values obtained experimentally is good. The maximum difference of temperatures at the depth of 0.02 m during summer period is 3°C, and at the depth of 0.10 m during autumn period is 1.5°C. In many cases it does not exceed 1°C. Insignificant shift between theoretical and experimental data can be explained by the fact that the actual values of heat conductivity coefficient and heat capacity of materials of pavement layers and soil differ from the accepted.

Figs. 7-8 show the diagrams with distribution of temperature in points of pavement and subgrade on July 25 and on October 23, 2013. From these drawings it is also visible that there is rather good compliance of calculated temperatures with experimental temperatures.

Thus, the results of the comparative analysis of experimental and calculated temperatures have shown that the developed model of non-stationary heat transfer defines a temperature field in a multilayered pavement design with high accuracy.

5. Long-term calculation of temperature in pavement points

The road section close to Kyzylorda was chosen for determination of regularities for variety of temperature field in pavement and subgrade for the long period of time. This road has the same pavement structure as the road close to Turkestan (Section 4). Therefore, their geometrical and physic mechanical characteristics are identical to Table 1. And technique of definition of temperature field in pavement and subgrade by the proposed mathematical model remains invariable. The only difference in this case, there are no experimental data for temperature. Long-term calculation of temperature in a road design is carried out on mathematical model only on the basis of data for air temperature. It is necessary to consider only the difference in geographic latitude, specific values of average wind speed in this area during the considered period of time and average time of sunrise and sunset near to Kyzylorda city for the same period.

So, the section of this article presents and discusses the results of calculations for temperature in points of pavement within three summer months from June 1 to September 1, 2010 with use of the developed model for the non-stationary heat transfer described in Sections 2 and 3 of this article.

The research area in the rectangle form with a width of 3.0 m and 2.4 m high was discretized on 420 plane quadrangular second order finite elements. Data for air temperature were taken

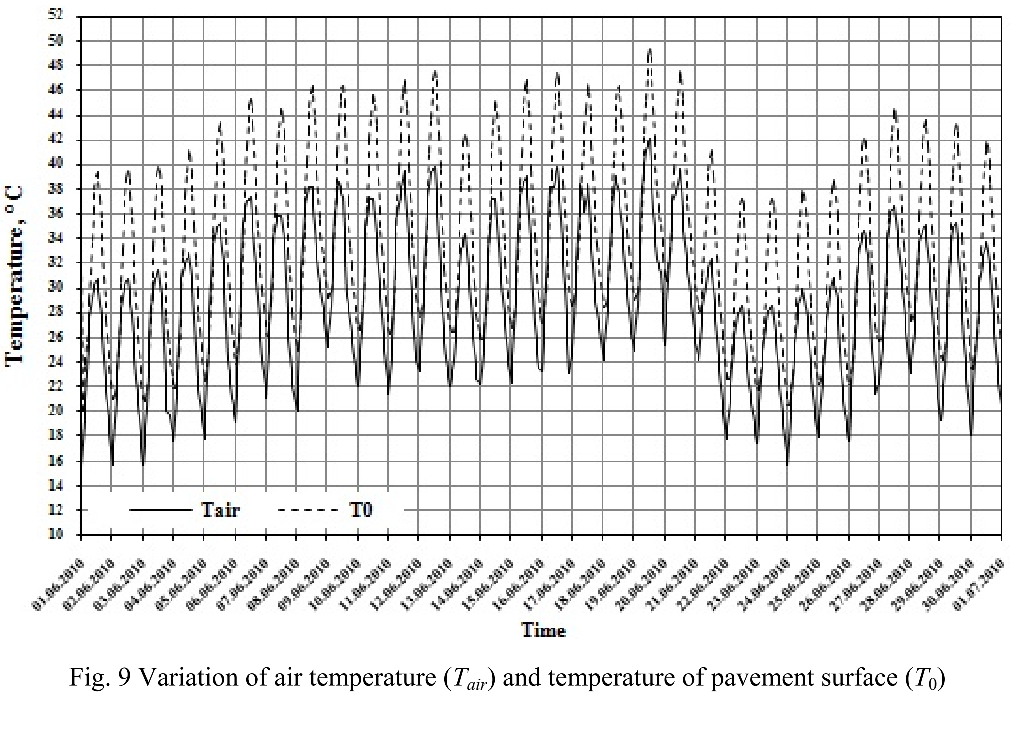
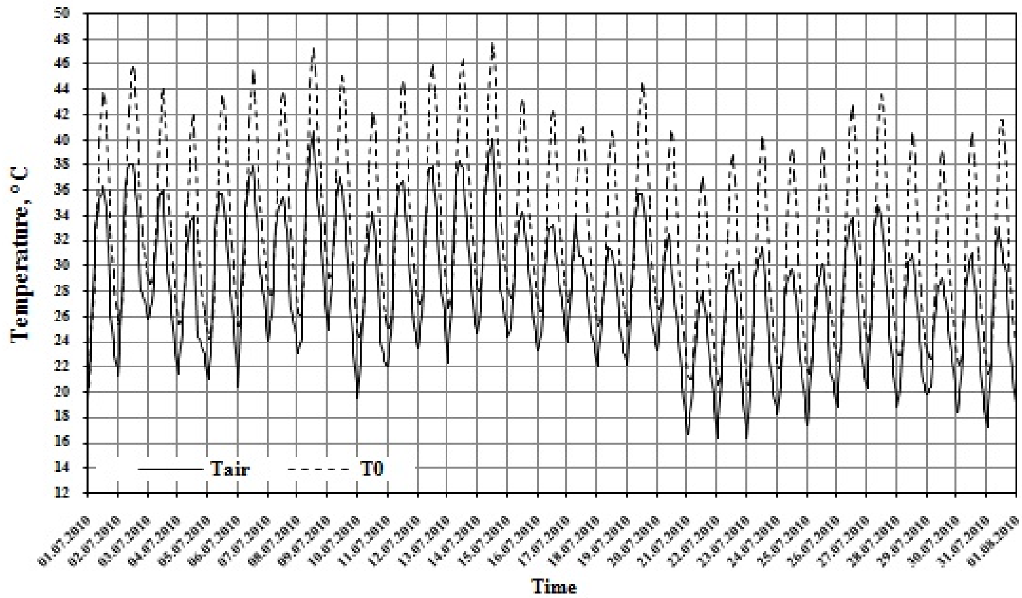


Fig. 9 Variation of air temperature (T_{air}) and temperature of pavement surface (T_0)



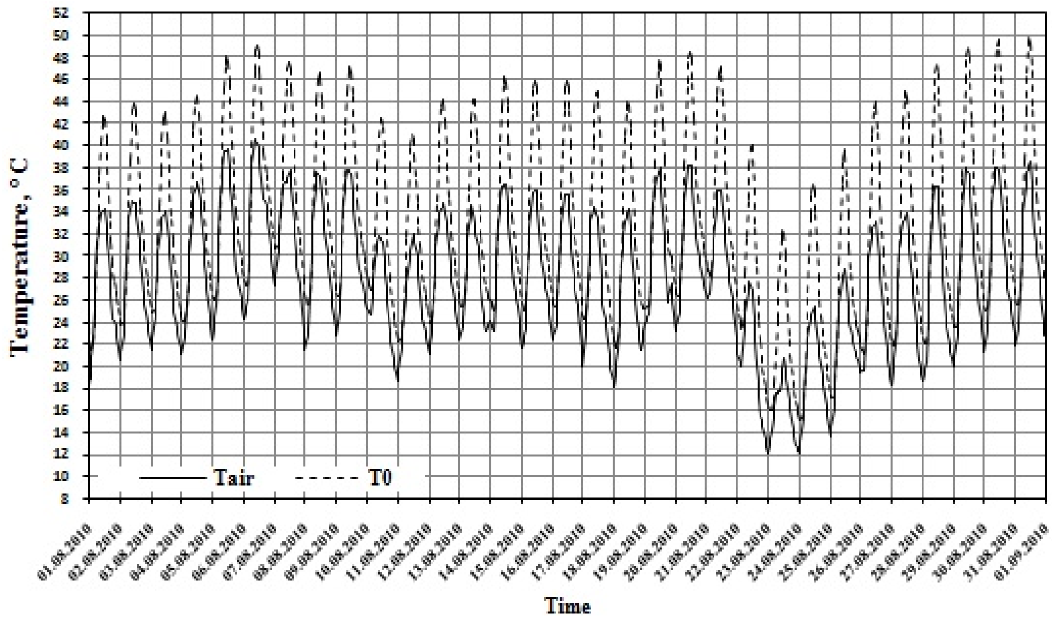


Fig. 9 Continued

from the meteorological station located in Kyzylorda city. Geographic latitude of the district α = 44°51′. Temperature at the depth of 2.4 m was accepted as constant and equal to 26.8°C which corresponds to average value of temperature at the considered depth, determined by experimental data carried out in the south of the Republic of Kazakhstan. Wind speed was accepted as equal to 3.1 m/s (SNIP 2005). According to meteorological researches (Abdullina 1989) for Kyzylorda city the time of sunrise (t_{sr}) and sunset (t_{ss}) were accepted as follows: June and July – t_{sr} = 4 hours 00 minutes; t_{ss} = 19 hours 00 minutes; August – t_{sr} = 5 hours 00 minutes; t_{ss} = 18 hours 00 minutes. For calculation of heat flow from total solar radiation the values of coefficients k_r, ε_a and ε_e were accepted as equal to 0.44; 0.55 and 0.9 respectively.

Figs. 9-10 show variation of air temperature, temperature of the surface of hot mix asphalt

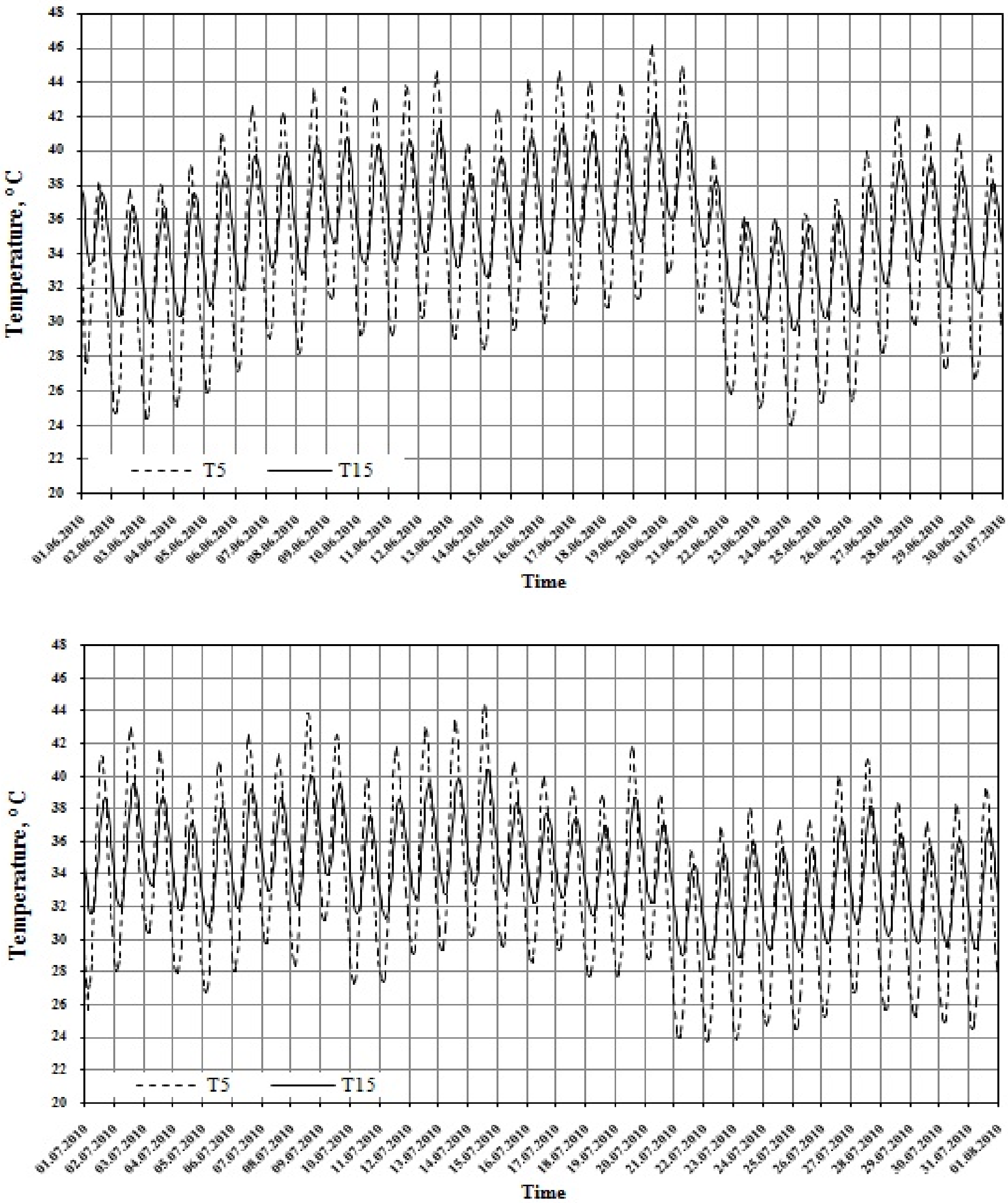


Fig. 10 Variation of temperature for asphalt concrete layers in the depth of 0.05 m (*T*5) and 0.15 m (*T*15)

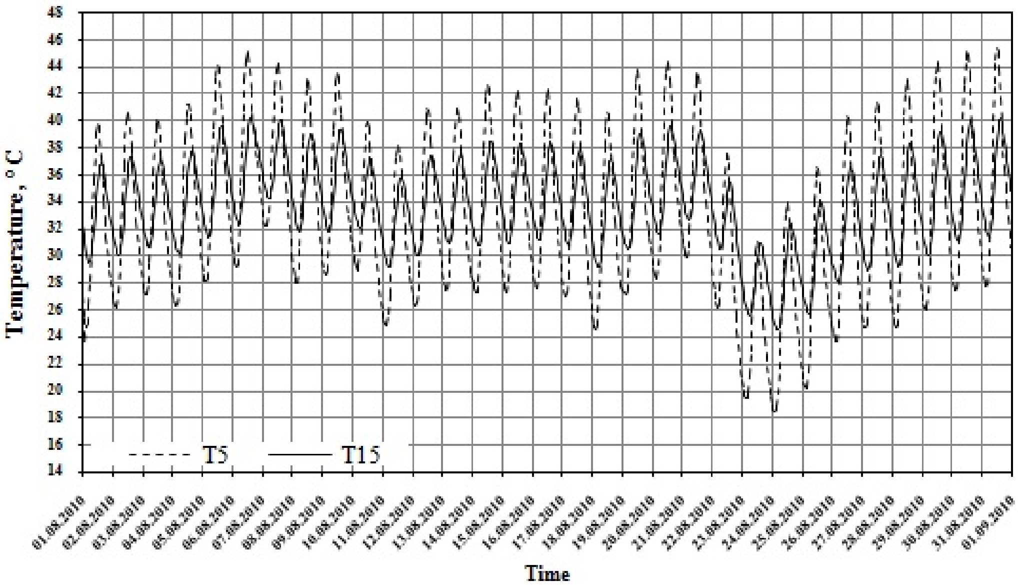


Fig. 10 Continued

pavement and temperature in the depths of 0.05 m and 0.15 m of asphalt concrete layers. Apparently, any change of air temperature causes corresponding change of temperature on the surface and in points of asphalt concrete layers. The maximum air temperature in June reached to 42°C, and in July and August 40°C. In these time points the maximum temperature on the surface of hot mix asphalt pavement was 48-50°C. At the depth of 0.05 m in the considered period of time the maximum temperature reached to 44-46°C, and at the depth of 0.15 m it reached to 40-42°C.

In the considered period air temperature at night fell to 12-16°C, and on pavement surface and at the depths of 0.05 m and 0.15 m to 16-20°C, 18-24°C and 24-30°C respectively.

Daily variation for air temperature is 20-22°C, on the surface of pavement and in the depths of 0.05 m and 0.15 m it is 16-18°C, 15-16°C and 7-8°C respectively.

Thus, it is determined that in summer hot months of the year in this region air heats up to 40-42°C, temperature of the surface of hot mix asphalt pavement reaches to 50°C. Amplitude of daily variation of temperature decreases with the depth. It decreases almost twice on the bottom surface of the second asphalt concrete layer (0.15 m), than on the surface of asphalt concrete pavement.

Wide temperature variation in asphalt concrete layers during daily cycle needs to be considered at the design stage of pavement.

6. Conclusions

(1) Mathematical model has been developed for non-stationary heat transfer in pavement and subgrade, which is based on solving of heat conductivity equation by the finite element method. This model considers conductive transfer of heat in the layers of pavement and subgrade, receiving heat from total solar radiation and atmosphere emission from the

surface of pavement and convective heat transfer.

(2) Accuracy of the model has been evaluated by comparison of temperatures, obtained theoretically and experimentally. Comparison showed sufficient high accuracy of the developed model.

(3) Stability of the developed model gave an opportunity to make long-term (within three months) calculation of temperature in pavement points, using the data of meteorological station for air temperature. The maximum absolute error is 2-3 °C.

(4) The results of the calculations showed that during summer period the temperature of asphalt concrete layers of pavement varied within wide range. It should be considered while pavement designing

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