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Article

A field-validated finite element framework for predicting transient temperature fields in multilayer pavements

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Abstract. Extreme continental climates in Kazakhstan impose large diurnal and seasonal thermal gradients in pavements, accelerating temperature-related distress. This study develops and validates a two-dimensional finite element model for predicting non-stationary temperature fields in multilayer pavement–subgrade systems from geographic location and climatic inputs. The transient heat-conduction problem with a surface thermal-balance boundary condition was implemented in MATLAB (PDE Toolbox). Validation used hourly temperatures from embedded sensors on the Kyzylorda-Shymkent (at km 2057) and Oskemen-Zyryanovsk (at km 0+075) highways during 1-31 July 2014. Predictions reproduced the attenuation of temperature amplitude with depth and closely matched measurements: coefficients of variation were <0.25 and correlations approached 1.0 at 2.1 m. Root mean square errors ranged from 0.44-7.49 °C and 0.26-5.65 °C for the two sites. The approach supports climate-resilient pavement design using readily available air-temperature data.
Keywords: temperature regime, non-stationary temperature field, numerical methods, finite element method, pavement.

1. Introduction

Highways are complex engineering systems that require consideration of numerous factors during their design, including the temperature regime [1]. In particular, the continental climate of Kazakhstan is characterized by a wide range of temperature fluctuations between winter and summer, low air humidity, and limited precipitation across most of the territory. Additionally, the northern regions experience long and harsh winters accompanied by short summers, whereas in the southern regions, winters are short and summers are prolonged and hot [2].

To enable long-term monitoring of temperature and moisture variations within pavement layers and the subgrade under different climatic conditions, three specialized measurement complexes were installed near Astana in 2010 [3]. These complexes were equipped with temperature and humidity sensors embedded in road sections with asphalt and cement-concrete pavements [4]. Later, in 2013, similar systems were installed near Oskemen, Almaty, Shymkent, and Atyrau [5].

The determination of the transient temperature field within pavement and subgrade layers of roads relies on mathematical modeling methods, which are widely applied worldwide in various forms [6]. All such approaches primarily use air temperature data as input. The determination of pavement surface temperature – essential for defining boundary conditions in mathematical models – is addressed differently by researchers [7]. Typically, the diurnal and seasonal variations in solar radiation intensity are first evaluated, which depend significantly on the geographic latitude of the location [8], [9]. In some cases, average seasonal wind speeds are incorporated, while in others, empirical relationships for convective heat exchange at the pavement surface are employed [10]. However, the applicability of these models is limited under the climatic conditions of Kazakhstan. Many existing pavement temperature prediction models were developed for regions with moderate climates and relatively stable humidity levels, and they often rely on empirical coefficients calibrated for specific geographic zones. In contrast, Kazakhstan is characterized by a sharply continental climate with extreme seasonal and daily temperature variations, low atmospheric humidity, and significant differences in solar radiation intensity across regions. These factors reduce the accuracy of models that do not explicitly account for regional climatic parameters and local thermophysical properties of pavement materials.

In recent years, approaches have been actively developed that combine the finite element method with climate models for analyzing thermal processes in road structures [11], [12]. These works demonstrate the potential for predicting temperature fields, considering the dynamics of climate change and regional peculiarities of heat exchange. In particular, the integration of data on solar radiation, humidity, and wind loads enhances the accuracy of modeling seasonal temperature fluctuations in road surface temperatures. It shows that the finite element method (FEM) is widely used in solving temperature-related problems for various pavement types [13], [14]. Moreover, FEM is applied to analyze the influence of climatic factors and material properties on pavement temperature and the near-surface thermal environment [15], [16]. The method's universality also makes it possible to combine temperature prediction models with mechanical property analysis for investigating thermally induced mechanistic behavior in pavement structures [17], [18]. Furthermore, FEM enables two- and three-dimensional heat transfer modeling, which is essential for analyzing planar thermal processes within pavement systems [19].

Therefore, this study aims to develop and validate a numerical model for predicting non-stationary temperature fields in multilayer pavement structures based on geographic location and climatic conditions. The model is verified using experimental data obtained from two highway sections: the "Kyzylorda-Shymkent" (km 2057) and "Oskemen-Zyryanovsk" (km 0+075) highways for the period 1-31 July 2014. The calculated results are compared with hourly temperature measurements recorded by embedded sensors.

2. Methods

The proposed model is verified based on the comparison of experimentally measured and numerically computed temperature values within pavement and subgrade layers.

First, the model determines the thermal balance on the road surface. The total heat flux incident on the pavement surface ($q(t)t$) results from the combined influence of various external factors, including the temperature difference between the ambient air and the pavement surface, which induces convective heat exchange between the two media [20], [21]. In general form, the total heat flux acting on the pavement surface (Figure 1) at any given time can be expressed as follows:

$$q(t) = q_k + q_c + q_s + q_a + q_e, \tag{1}$$

where: q_e – latent heat flux associated with moisture evaporation from the pavement surface, kW/m^2.

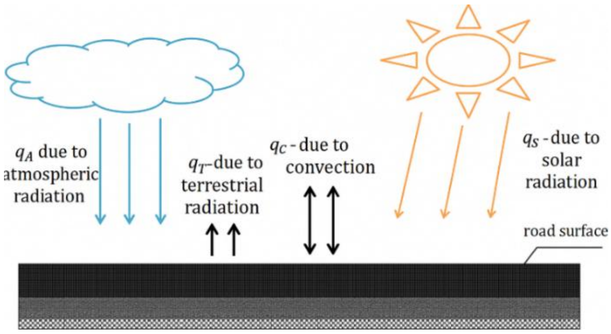


Figure 1 – Schematic representation of the total heat flux formation on the pavement surface

However, when solving the specific problem, the first term in Eq. (1) is excluded, since it is determined by the following expression:

$$q_k = -k\frac{T_d - T}{d} kTdT_d d, \tag{2}$$

where: k – coefficient of conductive heat transfer, W/(m·°C); T – temperature at the pavement surface point to be determined, °C; d – depth of the considered point within the pavement structure, m; T_d – temperature at a certain depth (d), °C.

Consequently, $q_k = 0$, because at the pavement surface $d = 0$ and $T_d = T$. Thus, the total heat flux acting on the pavement surface, which is required for defining the boundary condition of the Cauchy problem, is expressed as follows:

$$q(t) = q_c + q_s + q_a + q_e \tag{3}$$

The transient heat conduction in a plane (2D) solid body is described by a parabolic-type differential equation:

$$K_{xx}\frac{\partial^2 T}{\partial x^2} + K_{yy}\frac{\partial^2 T}{\partial y^2} + Q = \lambda\frac{\partial T}{\partial t}, \tag{4}$$

with the following boundary conditions:

$$K_{xx}\frac{\partial T}{\partial x} l_x + K_{yy}\frac{\partial T}{\partial y} l_y + h_c(T - T_в) + q = 0, \tag{5}$$

where: K_{xx} and K_{yy} – coefficients of conductive heat transfer along the coordinate axes, kW/(m·°C); h_c – convective heat transfer coefficient between the surface of the solid body and the surrounding air, kW/(m²·°C); T – unknown temperature of the body surface where convective heat exchange occurs, °C; Q – internal heat source within the body, kW/m³; T_a – known ambient air temperature, °C; l_x, l_y – directional cosines; q – heat flux intensity, kW/m²; $\lambda = c\rho$, where c is the specific heat capacity, J/(kg·°C), and ρ is the material density, kg/m³.

The differential equations and boundary conditions used in Eqs. (4) and (5) are based on the classical principles of the theory of unsteady thermal conductivity [22], [23] and implemented using finite element modeling techniques in accordance with [24], [25].

To solve Eq. (4), the variational principle is used, according to which, when the heat transfer process reaches its transient steady state, the amount of heat accumulated by the body at that moment attains its minimum value.

In this work, the method of approximate replacement of the partial time derivative with its finite-difference analog using a central difference scheme is applied. As a result, the differential equation is reduced to a system of linear algebraic equations:

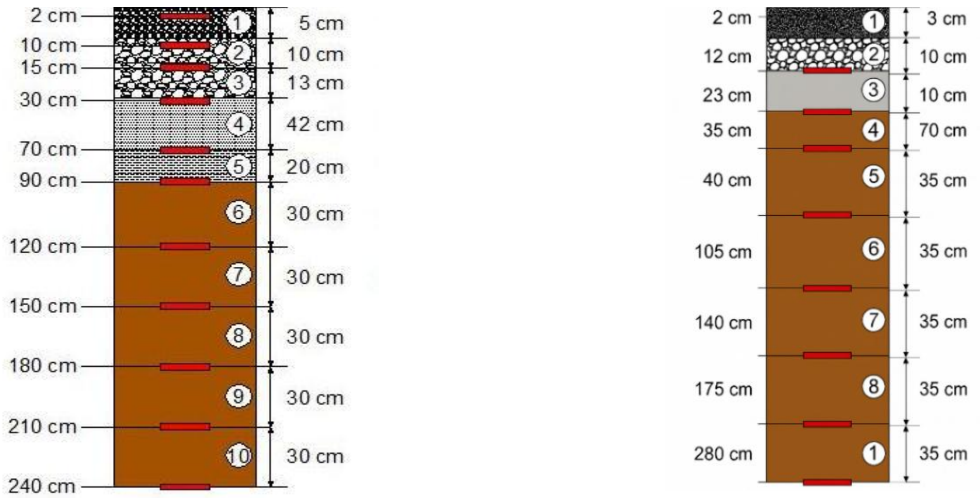
$$\left([K] - \frac{2}{\Delta t}[C]\right)\{T\}_0 - 2\{F\}^*, \tag{6}$$

where: $\{F\}^* = \frac{1}{2}(\{F\}_1 + \{F\}_0)$. Here, the nodal heat load vectors $\{F_0\}$and $\{F_1\}$ correspond to the time moments t and $t + \Delta t$, respectively ($\{T_0\}tt + \Delta t\{T_1\}\{F\}^*$). Assuming that the initial nodal temperature values at time are known, the nodal temperature values at time can be obtained by solving Eq. (6), respectively. The column vector contains known parameters; therefore, it can be calculated before solving Eq. (6).

The calculations were performed in the MATLAB environment using a custom script based on the standard PDE Toolbox libraries. An uneven grid with a depth step of 0.02-0.05 m was used for sampling. The criterion for the convergence of the iterative process was considered to be a change in the temperature of nodes of less than 0.001 °C in neighboring iterations. The correctness of grid independence was monitored by reducing the grid pitch by 50% and checking the stability of the results (< 1% discrepancy).

The proposed method for solving the transient heat conduction problem for a multilayer pavement structure was tested on the “Kyzylorda-Shymkent” highway section, at km 2057, near the city of Turkestan in the Turkestan region, and on the “Oskemen-Zyryanovsk” highway section, at km 0+075, between 1 and 31 July 2014 by comparing the calculated temperatures with experimental data obtained under similar climatic conditions. The validation of the results was performed by statistical analysis, including the estimates of the coefficients of variation, correlation factors, and the indicators of the root mean square error (RMSE), which together provided an opportunity to assess the reliability of the model and the degree of accuracy of its predicted values.

The “Kyzylorda-Shymkent” highway pavement structure consists of 6 pavement layers, and the “Oskemen-Zyryanovsk” highway – 3, constructed on a soil subgrade (Figure 2), with layer thicknesses and materials' physical, mechanical, and thermophysical properties shown in Table 1.



a) Kyzylorda-Shymkent b) Oskemen-Zyryanovsk

Figure 2 – Structure of the highway sections with a layout of temperature and humidity sensors

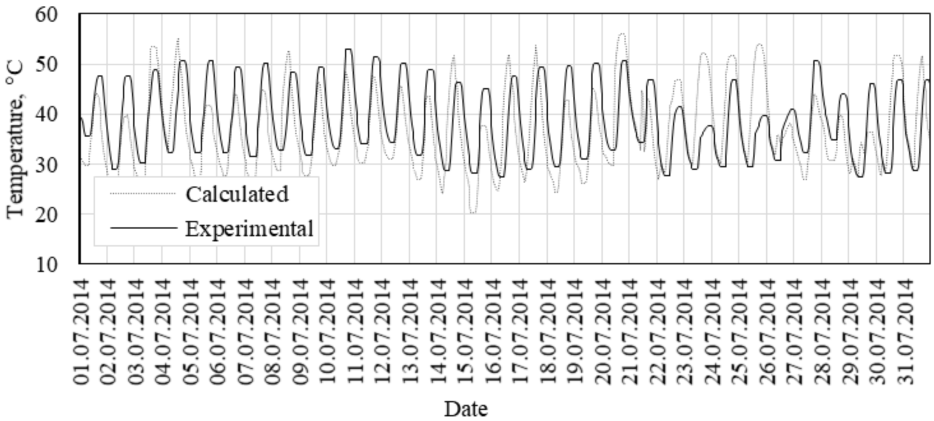
Table 1 – Characteristics of the layers

Layer No.	Material of the layer	Thickness, m	Thermal conductivity coefficient, W/(m·°C)	Specific heat capacity, J/(kg·°C)	Density, kg/m^3
	Kyzylorda-Shymkent highway section				
1	Fine-grained asphalt concrete	0.05	1.40	1650.0	2400
2	Coarse-grained asphalt concrete	0.10	1.25	1650.0	2300
3	Fine-grained asphalt concrete (old layer)	0.13	1.40	1650.0	2400
4	Coarse-grained cold asphalt concrete	0.42	1.25	1650.0	2300
5	Sand-gravel mix (fine)	0.20	1.80	1000.0	1400
6	Sand-gravel mix (coarse)	0.30	1.80	1000.0	1900
7	Subgrade soil (heavy sandy loam)	-	1.62	1450	200
	Oskemen-Zyryanovsk highway section				
1	Fine-grained asphalt concrete and bituminous binder	0.03	1.40	1650	2400
2	Cold asphalt concrete	0.10	1.25	1650	2300
3	Sand-gravel mix	0.10	1.80	1000	1900
4	Subgrade soil (heavy sandy loam)	-	1.62	1450	200

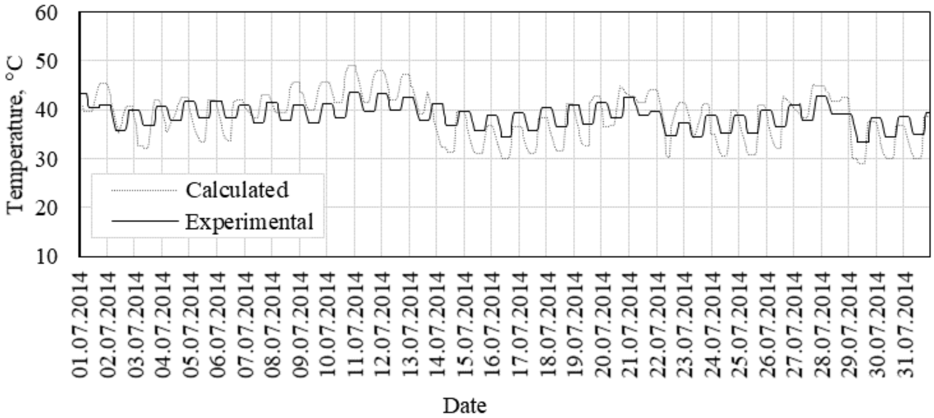
The Interpribor Company (Chelyabinsk, Russia) has manufactured temperature and humidity sensors at the order of the JSC “Kazakhstan Road Research Institute”. Each sensor, made in the form of a metal capsule, contains an element for measuring temperature based on the effect of thermal resistance and an element for measuring humidity through diamagnetic permeability [5]. The temperature elements of the sensors were calibrated by the manufacturer, and the moisture elements were tested by the JSC “Kazakhstan Road Research Institute” laboratory. Calibration of the sensors was carried out using the soils selected at their installation location.

3. Results and Discussion

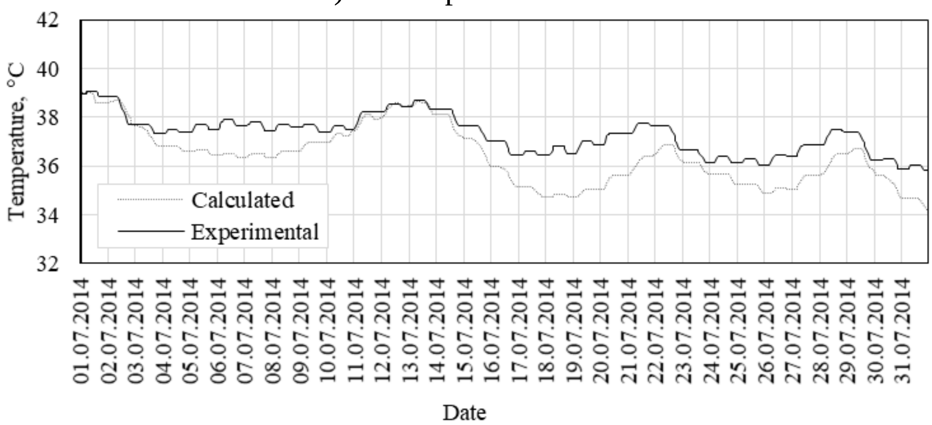
The results of comparison between the experimental data and the calculated results obtained using the MATLAB-based program for the “Kyzylorda-Shymkent” and “Oskemen-Zyryanovsk” highway sections, for the period 1-31 July 2014, are presented in Figures 3 and 4.



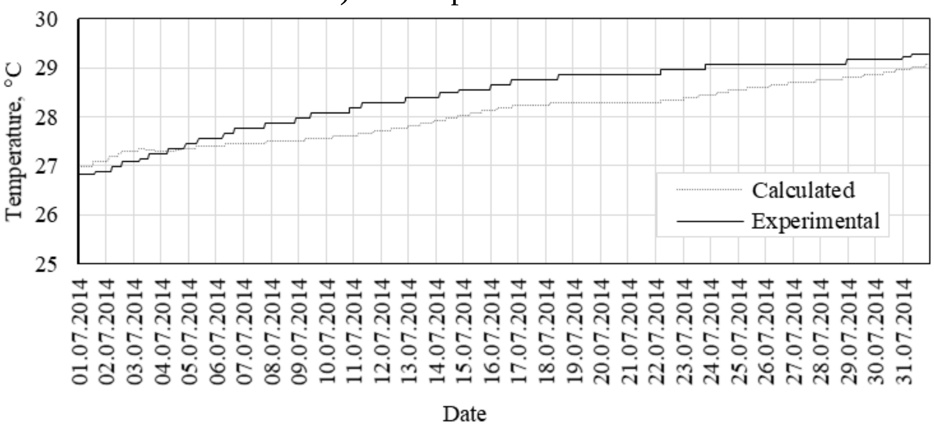
a) At a depth of 0.02 m (pavement surface)



b) At a depth of 0.15 m

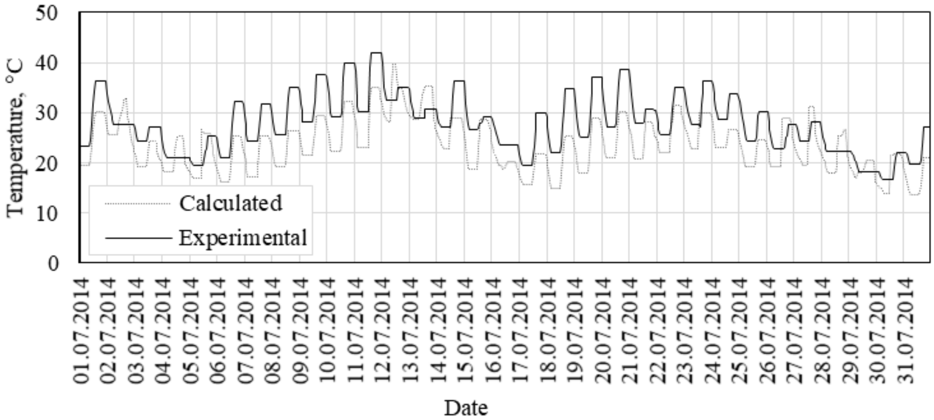


c) At a depth of 0.7 m

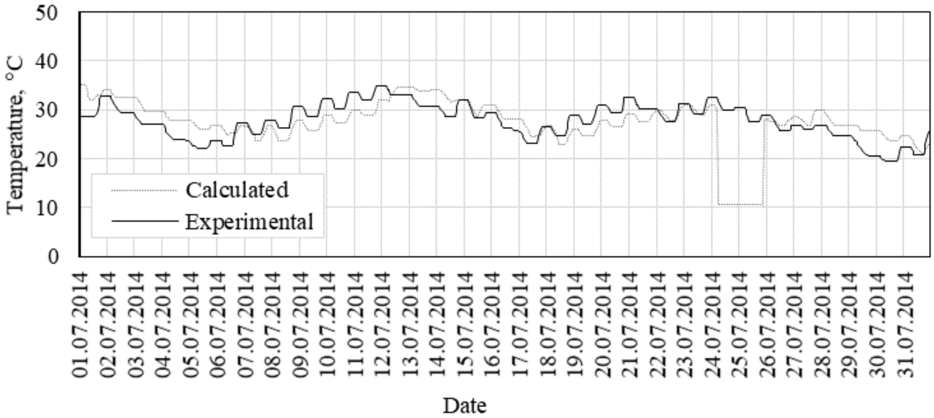


d) At a depth of 2.1 m

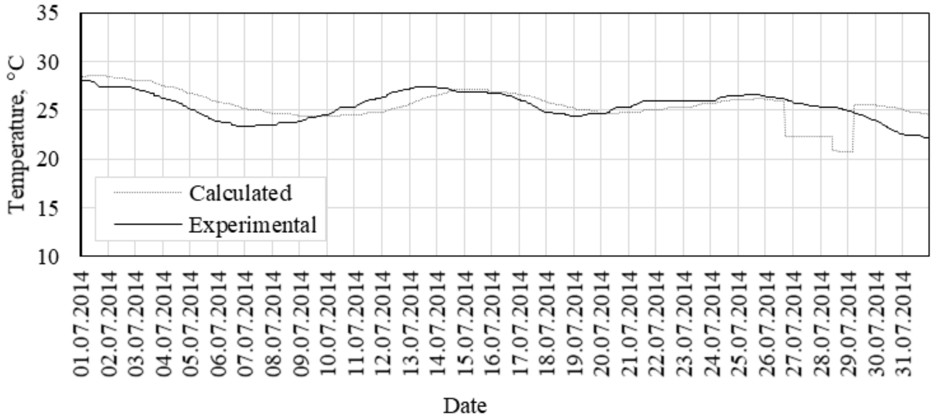
Figure 3 – Temperature values for the “Kyzylorda-Shymkent” highway section



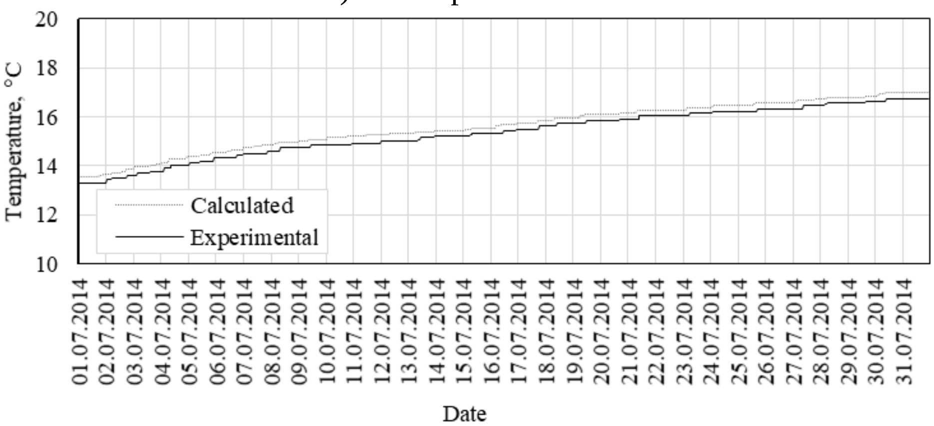
a) At a depth of 0.02 m (pavement surface)



b) At a depth of 0.23 m



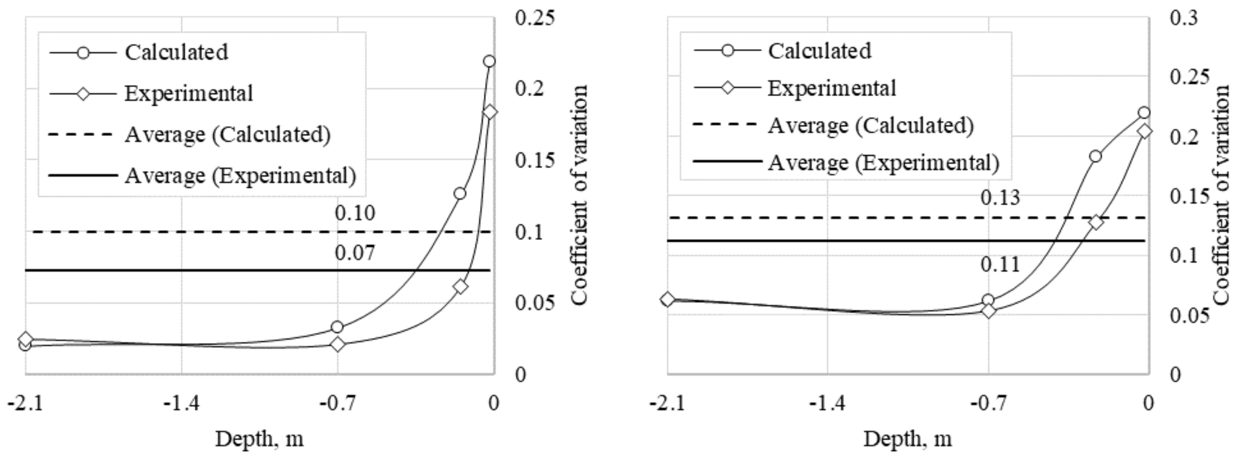
c) At a depth of 0.7 m



d) At a depth of 2.1 m

Figure 4 – Temperature values for the “Oskemen-Zyryanovsk” highway section

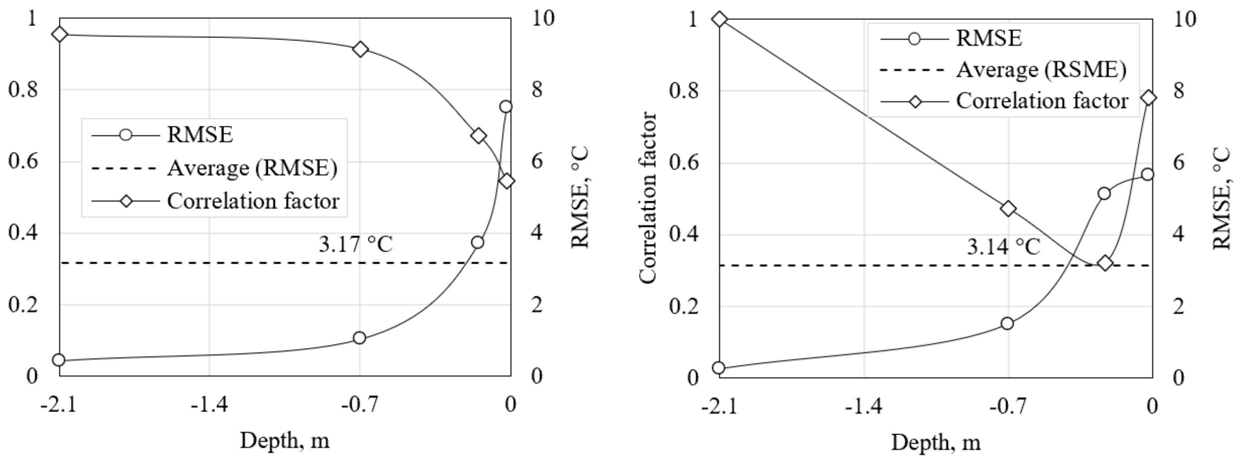
Figures 3 and 4 above demonstrate the temperature fluctuations over 31 days of July 2014 at the various depths between 0.02 and 2.1 m of the highway sections “Kyzylorda-Shymkent” and “Oskemen-Zyryanovsk”, respectively. In both sections, there is a noticeable trend toward a decrease in the amplitude of temperature fluctuations with an increase in measurement depth. It is also seen that the curves representing the calculated values of the temperature are very close to those of experimentally measured ones. The results of the statistical analysis in Figures 5 and 6 present more detailed insights into the significance of this proximity.



a) Kyzylorda-Shymkent b) Oskemen-Zyryanovsk

Figure 5 – Coefficient of variation

Figure 5 shows the coefficients of variation for the calculated and experimental values of temperature, which reveals the extent of their dispersion. Thus, for both highway sections, the coefficients of variation are less than 0.25, while their average values are at a low level and differ slightly. This may indicate a certain stability in the measurements with sensors (for experimental values) and in the estimates with the model (for calculated values). Overall, the decrease in the values of the coefficients of variation is observed with the increase in depth. To reflect the convergence between the calculated and experimental values, Figure 6 presents the results of correlation factor estimates along with the RMSE.



a) Kyzylorda-Shymkent b) Oskemen-Zyryanovsk

Figure 6 – Correlation factor and RMSE

Figure 6 shows that at greater depths, the calculated values of temperature correlate with experimental values for both highway sections. Thus, at a depth of 2.1 m, the correlation factor is really close to 1.0, and at a depth of 0.7 m, the correlation factor is still higher than 0.9 for the “Kyzylorda-Shymkent” highway section, but for the “Oskemen-Zyryanovsk”, it is around 0.5, decreasing to 0.3 at a depth of 0.23 m and rapidly increasing to 0.8 at a depths of 0.02 m, suggesting the influence of external factors during the run of the model (computer malfunctions, power surges). This pattern is clearly visible in Figures 4b and 4c, where deviant fluctuations of the calculated values of the temperature can be observed at depths of 0.23 and 0.7 m. Despite this occurrence, the RMSE values reflect pretty low ranges of 0.44-7.49 °C for the “Kyzylorda-Shymkent” highway section, and 0.26-5.65 °C for the “Oskemen-Zyryanovsk” highway section, averaging to 3.17 and 3.14 °C, respectively.

Overall, the results of comparing the calculated and experimental temperature values at the nodal points of the studied highway sections indicate the adequacy of the proposed mathematical model for describing the formation of the transient temperature field in the examined multilayer pavement structure. The slight discrepancy between the calculated and experimental results of the transient temperature field in the multilayer pavement structure may be attributed to the assumption regarding the intentional time shift applied when determining the nodal load vector [5].

Thus, the proposed method for solving the transient heat conduction problem makes it possible to determine the non-stationary temperature field in a multilayer pavement structure using only the time-dependent air temperature data for the period of interest, which can be obtained from a meteorological station located near the studied highway section. The developed model makes it possible to predict the temperature field for various road surface structures, taking into account the climatic parameters of the region, which can be used in the design of thermally deformable road surfaces and optimization of the composition of asphalt mixtures.

4. Conclusion

This study developed a two-dimensional finite-element framework to reproduce the non-stationary temperature field in multilayer pavement–subgrade systems using a surface heat-flux boundary condition derived from the pavement thermal balance and time-dependent meteorological input. The model was implemented in MATLAB (PDE Toolbox) with verified convergence and grid-independence controls, enabling stable transient solutions over the analyzed period.

Validation against hourly in-situ sensor records for two highway sections (“Kyzylorda-Shymkent” and “Oskemen-Zyryanovsk”) over 1-31 July 2014 showed that the computed temperature profiles closely follow measured trends across depths from 0.02 to 2.1 m, with attenuation of fluctuation amplitude with depth captured consistently. Statistical agreement indicators confirmed the adequacy of the approach: coefficients of variation were below 0.25, correlations improved with depth (approaching 1.0 at 2.1 m), and RMSE values remained within practical bounds (0.26-7.49 °C depending on depth/section).

From an engineering standpoint, the proposed model provides a practical tool for estimating internal pavement temperatures needed for thermally driven performance checks (e.g., material selection, seasonal construction/maintenance planning, and subsequent coupling with mechanistic response analyses). Remaining discrepancies are plausibly linked to input/measurement irregularities and simplifying assumptions in boundary/loading representation. Future work should extend the framework toward coupled heat-moisture processes, improved representation of external climatic actions, and three-dimensional simulations for complex geometries and localized effects.

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Kurmangazy Tileu – concept, supervision, methodology, analysis, editing.
Koblanbek Aytbayev – methodology, resources, interpretation, editing.
Adina Ainayeva – concept, data collection, drafting, communication, editing.
Beksultan Chugulyov – data collection, laboratory testing, visualization, analysis.

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