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Review Paper

TEMPERATURE ESTIMATION METHOD OF ASPHALT PAVEMENT IN HUNGARY

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Abstract. *Service life of the pavement can be predicted with proper temperature estimation of the pavement structure. Asphalt mixture displays a different modulus upon temperature change due to its viscoelasticity. The purpose of this study is to estimate such a temperature. Methodology in here includes one with the solution of heat conduction theory of the asphalt, and the other one statistical method. Results show that there is not a significant difference between the results made by two different methods. As a result of the model performance, the error range between the observed value and the predicted value is within the range suggested by other studies, so it is judged that the performance of the model is good. However, the prediction accuracy in the month with the highest and lowest temperatures per year was low. It seems that follow-up actions on this part will be necessary in the future. This study is expected to be used in various ways for road management in Hungary, and it is expected to be a basic study for the construction of road meteorological information system.*

Key words: *Asphalt mixture temperature, climatic load quantification, asphalt layer temperature estimation*

1. INTRODUCTION

Asphalt mixture shows a change in stiffness according to temperature, and thus shows behavior such as plastic deformation (e.g., rutting) and low-temperature crack in winter. Therefore, it is necessary to predict the temperature of the proper asphalt mixture to ensure the serviceability of the road. The internal temperature of the asphalt concrete pavement layer is determined in the form of temperature distribution by depth through a temperature prediction model based on the atmosphere temperature. Through the studies, it has been

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found that the factors that have the most influence on the asphalt pavement are air temperature and solar radiation.

There are two main ways to predict the temperature inside the asphalt. The first method is a prediction using regression analysis from actual data, and the second method is a prediction method based on heat conduction theory. Here, both methods are presented and the comparison between those two models is also presented.

In this study, a temperature prediction model for each depth of the asphalt pavement was prepared using the temperature distribution for each depth of the test road in Budapest, Hungary. The measurement devices were buried at 2 cm, 5 cm, and 10 cm from the pavement surface. The temperature of the asphalt pavement was recorded for a year and saved into a database.

The purpose of this study is to present basic data for the selection of appropriate asphalt for each region by establishing a temperature prediction model in the pavement according to temperature change, analyzing the change in the deformation coefficient according to temperature, and deriving the relationship between the atmospheric temperature and the deformation coefficient.

The algorithm for prediction of the internal temperature from the pavement surface temperature used finite difference method based on the heat conduction theory. By introducing and programming a numerical model to predict the internal temperature using the heat conduction theory, the measured data and the predicted data were compared and reviewed, and their applicability was verified.

2. Background

In the United States and other countries, research on road surface temperature and temperature by pavement depth and model development are active.

The temperature of the pavement is determined by the external conditions such as insolation, atmospheric temperature, wind speed, precipitation, cloud coverage, water content of subgrade. The internal conditions by type of the binders also have an effect. Dickinson employed such external climatic conditions into the estimation of the asphaltic pavements' temperature [1]. Saas developed a Road Condition Model embedded in the automatic road temperature prediction system promoted by the Danish Meteorological Institute. The results of this study demonstrated that the sensitivity of temperature prediction showed a significant dependence on atmospheric meteorological data [2]. In Canada, a system called METRo was developed for research purposes at the request of the Canadian weather center. The advantage of this system is that it can use the weather and road temperature observation values collected from the road meteorological information system and the weather data predicted from the Canadian weather center's own model. At the same time, it can explain the accumulated state of water in the liquid or solid state on the road surface [3].

In terms of the heat balance, the temperature of the pavement surface is higher than the atmospheric temperature, so a temperature gradient toward the atmosphere occurs. The temperature change of the pavement surface due to solar radiation can be expressed in the form of Haversine curve [4]. Barber [5] assumed that the pavement could be modeled as a semi-infinite mass exposed to the effective air temperature. The author assumed that the maximum surface temperature can be expressed as a sinusoidal function, and the contribution of solar radiation to the average effective air temperature was quantified.

Solar energy from the sun at any time on the surface of the pavement is [4]

$$I(t) = \frac{2s}{t_1} \sin^2 \frac{\pi t}{t_1} \tag{1}$$

S: total insolation for a day (Wh/m^2), t_1: time (h, set as 0 at 1 hour before sunrise), t: time

At any time on the surface of the pavement, the convective energy between the surface of the pavement and the atmosphere is

$$E(t) = h_c[T_a(t) - T_s(t)] = h\Delta T(t) \tag{2}$$

h_c: coefficient of surface thermal transfer ($W / m^{2o}K$, T_a: air temperature (°K), T_S: surface temperature (°K°)

Thus, the energy flux can be stated as,

$$\gamma I(t) - E(t) \tag{3}$$

γ: absorptivity of the surface for solar radiation

When calculating the surface temperature and the internal temperature of the pavement, it is convenient to start from the time when the temperature inside the pavement is the same as visually there is no temperature gradient inside the pavement.

A quadratic equation for the maximum and minimum pavement temperature which considers the latitude is suggested by [6] based on the energy balance.

$$q_{net} = q_s + q_a - q_c - q_k - q_r = 0 \tag{4}$$

q_s: direct solar radiation, q_a: atmospheric radiation, q_c: convection energy, q_k: conduction energy, q_r: radiation energy emitted from the surface

From the net energy balance of pavement structure, Solaimanian and Kennedy proposed the quadratic equation for the maximum pavement surface temperature prediction [6].

$$R_0 \cdot \alpha_1 \tau_a^{\frac{1}{\cos z}} \cos z + \varepsilon_a \sigma T_a^4 + h_c(T_s - T_a) - \frac{k}{x}(T_s - T_x) - \varepsilon\sigma T_s^4 = 0 \tag{5}$$

R_0: solar constant (1367 W/m^2), α_1: solar absorptivity (asphalt concrete: 0.85 ~ 0.93), τ_a: transmission coefficient (clear day =0.81, cloudy day = 0.62), z: Zenith angle, ε_a: coefficient of atmospheric radiation, σ: Stefan-Boltzman constant (5.67×10^{-8} $W/m^{2o}K^4$), k: thermal conductivity (1.36 W/m^oC), T_x: temperature at depth x.

The minimum surface temperature can be derived from equation (11) by eliminating the $q_s q_s$ term since the minimum temperature appears at the night without the sun.

$$\varepsilon_a \sigma T_a^4 + h_c(T_s - T_a) - \frac{k}{x}(T_s - T_x) - \varepsilon\sigma T_s^4 = 0 \tag{6}$$

Inside of the asphalt pavements, the temperature prediction is a transient problem. Straub et al. established a pavement temperature model for the atmospheric temperature and introduced an analysis method using the finite difference method. The temperature gradient at the time of calculation and the pavement temperature from the distribution of 24-hour temperature are analyzed [7].

3. Measurement

Temperature was measured in central Hungary. The sensor implanted on the test road collects the pavement's surface temperature and temperature at the certain depth (2, 5 and 10 cm) by 20 minutes of interval. The surface temperature distribution can be found in figure 1, and the monthly average temperature is described in table 1.

Table 1 Monthly Average Surface Temperature (°C)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
4.21	4.38	8.36	10.87	16.31	24.22	24.26	26.26	16.95	15.24	14.07	4.58

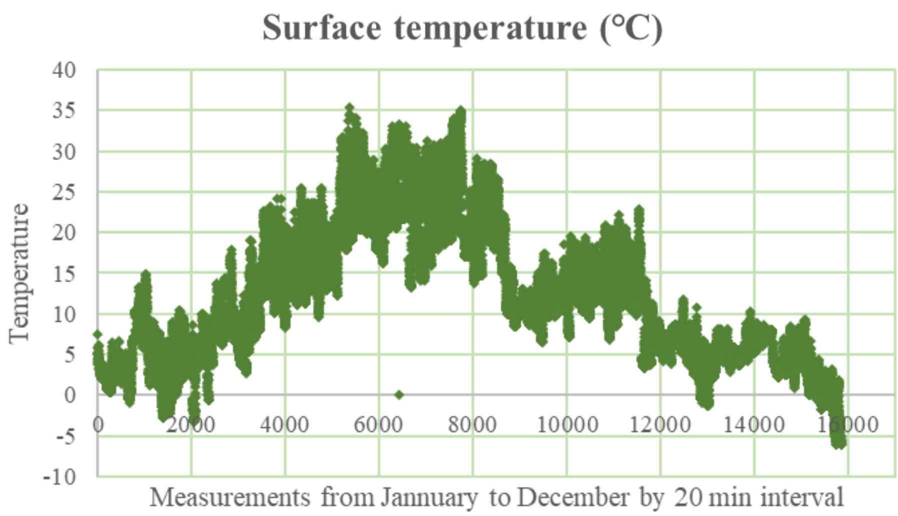

Fig. 1 Title of figure Surface temperature distribution of Budapest, Hungary

The surface temperature of Hungarian road does not exceed minimum -10 ºC or maximum 40 ºC. Based on this appearance, the temperature estimation model using statistical method uses 11 subdivisions [8] (following section 4.2).

4. Temperature Estimation Method of Asphalt Pavement in Hungary

4.1. Pave-ut, a program for temperature estimation along the depth for Hungary

This program takes two main steps, which are first subroutine for surface temperature estimation and second subroutine for temperature estimation along the depth. For the validation, in this study only the 2, 5 and 10 cm depth points were chosen. The first subroutine is to find the solution of the heat-energy balance equation which describes heat transfer between surface and air. The second subroutine is to reflect the energy conduction of the asphalt mixture.

As Dickinson suggested the estimated values do not exceed ± 3 ^oC by the real value [1], the time steps and spatial discretization were done. The surface temperature of the pavement body can be obtained from the energy flux (equation 3), which is the difference between the absorbed heat and emitted heat and was solved by substituting environmental factors in Hungary.

For the prediction of the internal temperature change, the initial reference temperature of the pavement should be set as a boundary condition (equation 5,6). The other boundary condition is the temperature at the bottom of the asphalt concrete layer. Here in this study the base is assumed as the insulator, the temperature inside of the asphalt concrete layer does not transfer to the base layer.

Temperature prediction within the pavement depth is a transient problem. To predict the temperature change inside the pavement from the surface temperature change, the partial differential equation of heat conduction (equation 7 [9]) was solved by the finite difference method, which is one of the numerical analysis methods. In this study, Crank-Nicolson implicit method is used.

$$\rho C_v \frac{\partial T}{\partial t} - \nabla(kT) - S = 0 \tag{7}$$

ρ: density (2.24 t/m^3), C_v: specific heat, S: energy change

The solution by the finite difference method of this equation is developed as the following equations. To exploit the finite difference method, the space of the asphalt concrete layer is divided into the finite spatial element Δx and time Δt. The i is the location of the time node, and m is the location of the spatial node.

Temperature change with time on the surface (difference equation)

$$\gamma I(t) + h(T_a - T_o^i) + \kappa \frac{T_1^i - T_o^i}{\Delta x} = \rho C_v \frac{\Delta x}{2} \frac{T_o^{i+1} - T_o^i}{\Delta t} \tag{8}$$

ρ: density (2.24 t/m^3), κ: thermal conductivity (W / m^oK), h: specific heat (840 Ws/kg^oK)

And the temperature at the bottom of the asphalt layer estimation done with energy conservation is

$$\kappa \frac{T_1^i - T_o^i}{\Delta x} = \rho C_v \frac{\Delta x}{2} \frac{T_o^{i+1} - T_o^i}{\Delta t} \tag{9}$$

With the boundary conditions described in equation 14 and 15, the temperature inside of the pavement can be estimated.

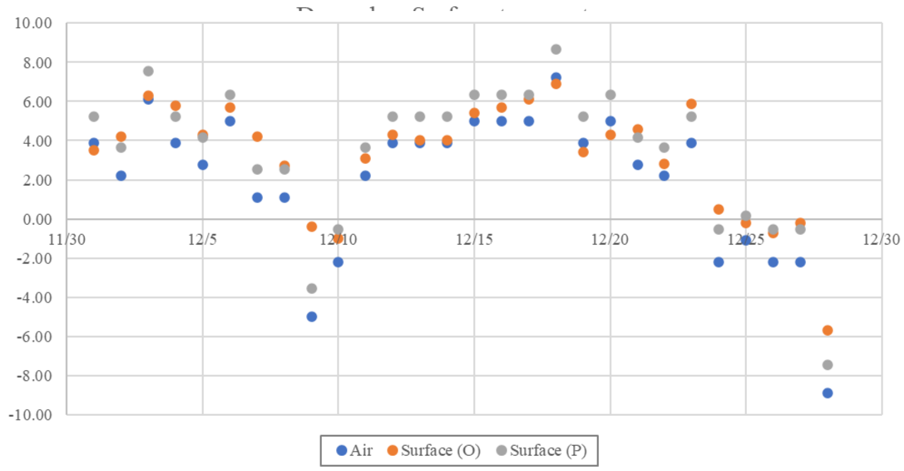

Fig. 1 Surface temperature distribution of December (O) and its prediction values (P)

Figure 2 shows the difference between the observed surface temperature (indexed as O) and predicted value (indexed as P). The surface temperature is always higher than the air temperature.

The material properties used for Hungarian climatic condition are shown below on the table 2. The input variables required for model performance were set as local values of Budapest.

Table 2 Thermal Equilibrium Equation Input Variables for Hungary condition

Index	Value
Solar absorptivity $(\alpha_1\alpha_1)$	0.9
Emissivity $(\varepsilon\varepsilon)$	0.9
Thermal conductivity (kk)	1.36 (W/m^oC)
Transmission coefficient	0.7
Thermal diffusivity $(\alpha\alpha)$	$\begin{cases}\text{day } 0.7\\ \text{night } 0.89\end{cases}$
Surface heat transfer coefficient	$\begin{cases}\text{day } 19.8\ (W/m^oC)\\ \text{night } 8.3\ (W/m^oC)\end{cases}$
Solar constant	1349 (W/m^2)

The finite difference method is a method of solving a differential equation as an algebraic differential equation under general boundary conditions, and the temperature of the center can be known [9]. The discretization of the space and time is done with the mesh size of $\Delta x = 0.2\,\Delta x = 0.2$ and $\Delta t = 0.2\,\Delta t = 0.2$. Here in this study the temperature distribution solution is done with the Crank-Nicolson implicit method (equation 10).

$$-\left(\frac{\alpha\Delta t}{\Delta x^2}\right)u_{i-1,j+1}+2\left(\frac{\alpha\Delta t}{\Delta x^2}\right)u_{i,j+1}-\left(\frac{\alpha\Delta t}{\Delta x^2}\right)u_{i+1,j+1}=\left(\frac{\alpha\Delta t}{\Delta x^2}\right)u_{i-1,j}+2\left(\frac{\alpha\Delta t}{\Delta x^2}\right)u_{i,j}+\left(\frac{\alpha\Delta t}{\Delta x^2}\right)u_{i+1,j} \quad (10)$$

Based on the finite different equation described above (equation 16), a program (Pave-ut) is built with Matlab. The temperature prediction results will be applied into the further structural analysis of pavement system as an input.

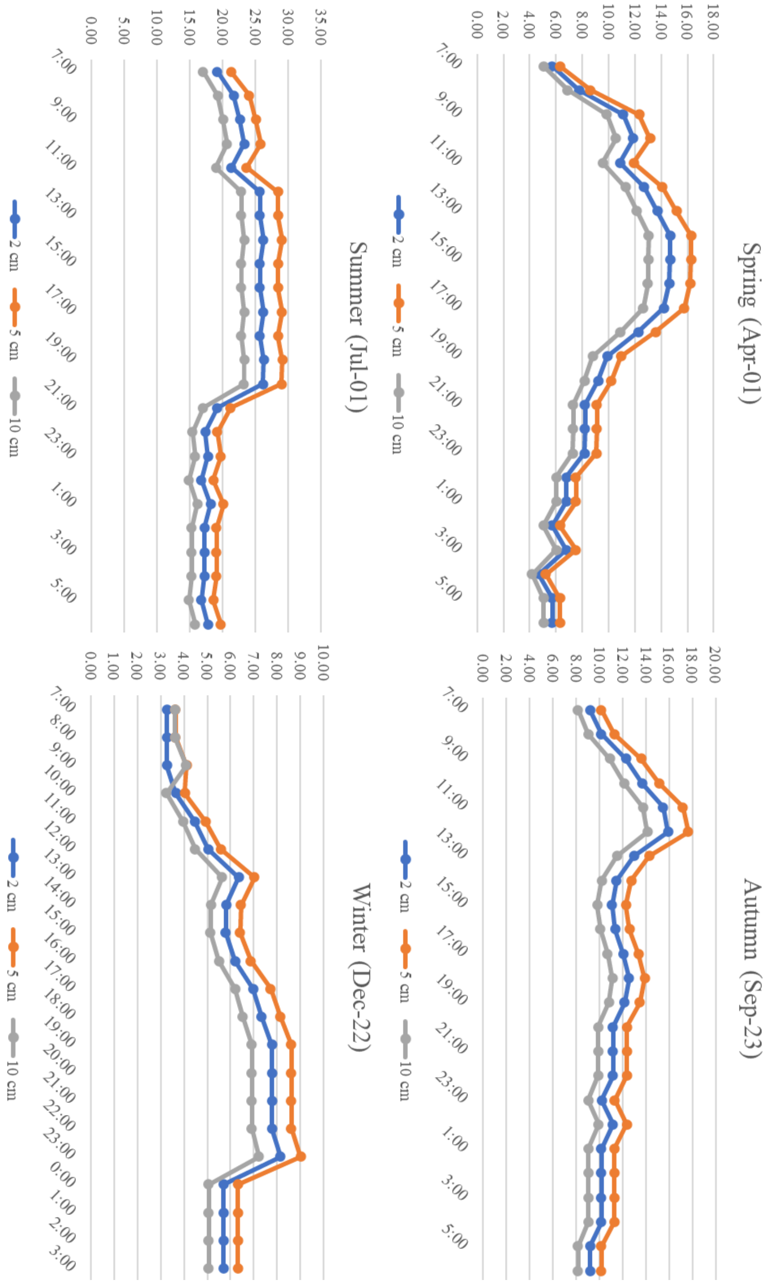

Fig. 2 Temperature gradients of Hungary

Figure 3 displays the temperature gradients of Hungary.

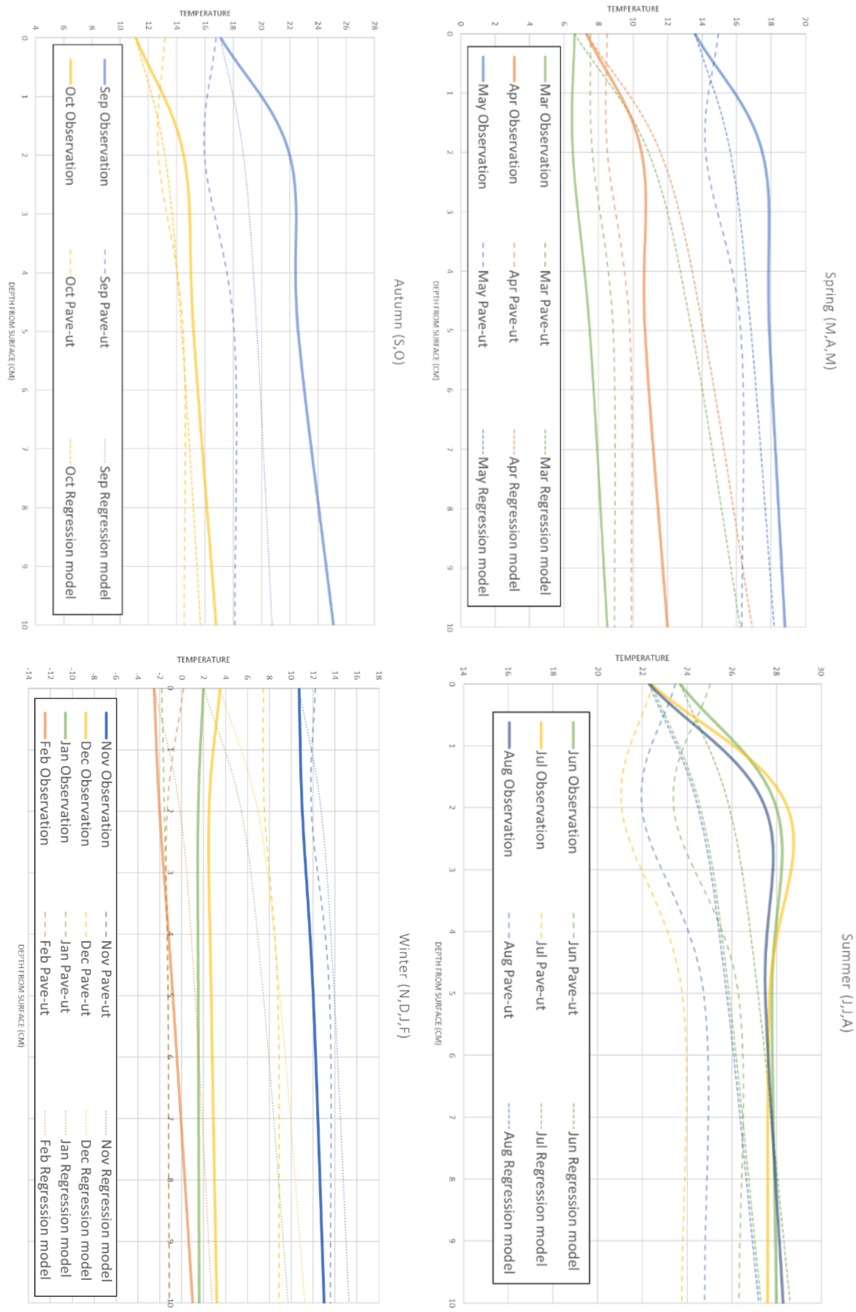

Fig. 3 Comparison of temperature gradient of two models (equation 15, equation 17)

4.2. Statistical Temperature Prediction Model for the Hungarian Road

There are two main streams to estimate the asphalt mixture's temperatures including the method based on heat transfer theory [4] and method based on historical data of that region [5]. The latter method uses the recorded observations and makes a regression model of it. The previous study of the authors used the second method, dealing with the statistical temperature model for Hungary [8]. This model is developed with the regression of the one year measured data. A measured data is subdivided into 11 subdivisions by the surface temperature, and the model coefficients are prepared for each of those. For the simplicity in the formation a square root function is used to represent the temperature distribution along the depth.

$$y = a \cdot \sqrt{x} + T_0 \tag{11}$$

where, y is asphalt temperature (°C) at depth x (cm), T_0 is surface temperature (°C), and a is a parameter as a function of T_0 which is shown in table 4.

Table 3 Model coefficient α as a function of surface temperature

Surface Temp [°C]	≤0	≤5	≤10	≤15	≤20	≤25	≤30	≤35	≤40	≤45	<45
a [-]	1.669	2.446	3.044	1.449	1.154	1.553	1.086	-0.9228	-1.3158	-2.0504	-3.5124
R2	0.9969	0.9938	0.9773	0.9819	0.9949	0.8528	0.6896	0.7139	0.9162	0.8445	0.8948

The predicted values with the model (equation 11) are shown in Fig. 4. The model shows a good level of prediction accuracy (Fig. 4).

4.3. Comparison between the pave-ut model and statistical model

Figure 4 shows the results of specific months with two different models. Comparison is made based on data of 7 AM on the 1st of every month, however January is compared based on 15th due to the lack of observation data. The regression model (equation 11) predicts the internal temperature of the asphalt layer as the function of the surface temperature. Whereas the model introduced here (equation 10) uses the air temperature.

5. CONCLUSION

This study is prepared for the mechanistic-empirical design method of the Hungarian pavement system. The necessity of environmental load quantification cannot be too emphasized in modern pavement structural design. A new asphalt layer temperature model is introduced and a comparison with the former model using regression method is done in this study. From the result, a more accurate structural design and serviceability are expected.

Below are the findings of this study:

1) The result of the estimation shows an acceptable difference (within 3℃ as stipulated in the literature).
2) The prediction accuracy in the month with the highest and lowest temperatures per year was low.

3) The regression model has a good level of internal temperature prediction with simple form as it is. However, since the model uses the surface temperature, it is difficult for general application without knowing the road surface temperature.
4) There is not a significant difference between the results calculated by two different methods.

The modeling of the pavement structure can be done better with properly estimated temperatures along the depth. This research provides a methodology for the estimation of the pavement layer's inside temperature by using the real historical data of Hungary. However, the measured data set used in this study is limited in one year and the input variables for heat conduction solution are found in the literature. Therefore, to improve the method to predict the pavement temperature more accurately, a long-term measurement of more than one year is required in a more systematic way and of the thermal characteristic variables of Hungary as well. The results of this study can be applicable as the input of the mechanistic-empirical design of the Hungarian pavement system.

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TEMPERATURNA METODA PROCENE ASFALTNIH KOLOVOZA U MAĐARSKOJ

Vek trajanja kolovoza može se predvideti pravilnom temperaturnom procenom kolovozne konstrukcije. Asfaltna mešavina pokazuje različite module pri promeni temperature zbog svoje viskoelastičnosti. Svrha ove studije je proceniti takvu temperaturu. Metodologija ovde uključuje jednu metodu sa rešenjem teorije toplotne provodljivosti asfalta, i drugu statističku metodu. Rezultati pokazuju da nema značajne razlike između rezultata dobijenih dvema različitim metodama. Kao rezultat performansi modela, raspon greške između uočene vrednosti i predviđene vrednosti je u rasponu koji su predložile druge studije, pa se procenjuje da je učinak modela dobar. Međutim, tačnost predviđanja u mesecu sa najvišim i najnižim temperaturama u godini bila je niska. Čini se da će ubuduće biti potrebne naknadne aktivnosti u tom delu. Očekuje se da će se ova studija na različite načine koristiti upravljanju putevima u Mađarskoj, a očekuje se da će biti i osnovna studija za izgradnju putnog meteorološkog informacionog sistema.

Ključne reči: *temperatura asfaltne mešavine, kvantifikacija klimatskog opterećenja, procena temperature asfaltnog sloja*