

## PREDICTING TEMPERATURE DISTRIBUTION IN HANOI REGION'S ASPHALT PAVEMENT THROUGH NUMERICAL SIMULATION

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### Abstract

This article presents determining the temperature distribution in asphalt pavement in the Hanoi area based on numerical simulation using FEM. Climate data were collected from freely available online data from the Federal Highway Administration of the United States. From this data, the surface temperature of the pavement was calculated, which served as the boundary condition for the heat transfer problem of the pavement. The results show that the pavement surface temperature is typically highest around 11 a.m. to 12 p.m., while the lowest temperature is typically around 4 a.m. to 6 a.m. The temperature inside the pavement layer is usually high between 10 a.m. and 4 p.m. when the strength and deformation resistance of the pavement are relatively low. In contrast, the temperature inside the pavement is low during the period between midnight and 6 a.m., when the asphalt concrete becomes brittle and is easy to crack. The analysis of the temperature distribution in the pavement structure can be used for calculating and designing the pavement, as well as predicting pavement rutting.

**Keywords:** Asphalt pavement; pavement surface temperature; temperature distribution; finite element method.

### 1. Introduction

In the process of exploiting asphalt pavement, the characteristics of the material in favor of elasticity or plasticity depend on temperature and loading conditions. This is because, in asphalt concrete mixture bitumen is a constituent material that is highly sensitive to temperature changes. Concretely, at high temperature, the asphalt concrete softens and can be easy to melt under loading. In contrast, at low temperature, the asphalt concrete hardens, but becomes brittle. With the properties of such asphalt concrete, shear deformation and rutting appear commonly in the asphalt pavement under high ambient temperature.

Because the properties of the asphalt concrete depend on temperature, the mechanical parameters of the material are usually determined at a certain temperature. In the other words, the temperature becomes a quantity to establish the quality assessment standards of the asphalt concrete. In the Marshall test used to evaluate the

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plastic deformation resistance of the material and in the Hveem test used to determine the cohesion or tensile properties of asphalt mixtures, the temperature is chosen at 60°C. The tests to determine the dynamic complex modulus and the indirect tensile elastic modulus under cyclic loads were carried out at three different temperatures of 5°C, 20°C and 40°C, respectively. These are the temperatures corresponding to the normal working conditions of asphalt concrete, i.e. cracking due to tensile stress at low temperature of 5°C and plastic deformation and shearing at high temperature of 40°C. For these reasons, it is necessary to determine the temperature distribution in the asphalt pavement structure.

The temperature distribution in the asphalt pavement depends on the thermal properties of the paving materials and the climatic conditions of the road construction area. The climatic conditions in each road construction site are different, thus having their own influence on the temperature distribution in the pavement [1, 2].

The pavement temperature can be predicted by a regression model, for example in the Superpave method [3, 4]. According to this method, we need to collect a lot of data to build a database and set up regression equations to suit the climate conditions in Vietnam. In some other studies, the authors modeled the change of pavement temperature by the problem of transient heat transfer. Differential equations of multilayer heat transfer problems can be solved analytically as in [5] or by numerical methods such as finite difference method [6, 7], finite element method [8-10] and the finite volume method [11]. So far, a temperature prediction based on the numerical methods for the asphalt pavement in Hanoi area is still not referred.

In the article, the authors calculate and predict the temperature of the asphalt concrete pavement in Hanoi area. The ambient temperature data is collected from a freely available online data provided by the Federal Highway Administration of United States. The temperature of asphalt concrete pavement in depth is calculated based on the problem of transient heat transfer by finite element method.

## **2. Equations of heat transfer**

To determine the temperature ( $T$ ) in a body, it is necessary to establish the relationship of temperature with coordinates and time ( $\tau$ ), which is the differential equation of thermal conductivity. The differential equation for heat conduction through a homogeneous, isotropic, and unsourced body has the following form [12]:

$$\frac{\partial T}{\partial \tau} = a \cdot \nabla^2 T \quad (1)$$

where  $a$  is the thermal diffusion coefficient determined by the expression:  $a = \lambda / \rho C_p$  with  $\lambda$  thermal conductivity,  $\rho$  unit weight and  $C_p$  specific heat of the material;  $\nabla^2$  stands for Laplace operator and has the following expression:

$$\nabla^2 T = \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) \quad (2)$$

In order for differential equation (1) to have a definite solution, it is necessary to have initial and boundary conditions.

In this study, one uses the following boundary conditions:

Boundary conditions of type 1, also known as Dirichlet conditions, show the law of temperature distribution on the surface of the body:

$$T = T_w \text{ on } S_1 \quad (3)$$

Boundary conditions of type 2, also known as Neumann conditions, indicate the heat flux density on the surface of the body:

$$q = -\lambda \frac{\partial T}{\partial n} = C \text{ on } S_2 \quad (4)$$

where  $\vec{n}$  is normal vector of the surface  $S_2$ ,  $C$  is a known value that may remain constant or change. If the surface is insulated or adiabatic, one will also consider  $C = 0$ .

### 3. Determination of pavement surface temperature

Based on a numerical method, in order to predict temperature field in the asphalt concrete pavement structure, it is necessary to determine the temperature of the pavement surface, which is generated mainly from solar energy.

There are many methods for determining pavement surface temperature. The field experimental method measures the actual temperature on the pavement surface. The experimental mechanical method combines the field measurements and the regression method to build the surface temperature calculation functions depending on the construction area. Formulas of semi-theoretical method for determination of pavement surface temperature are developed with adjustment coefficients drawn from experiments. In this study, the authors use latter method to determine the temperature of pavement surface [13]. Accordingly, the surface temperature of asphalt concrete pavement in a day-night cycle can be determined by the following formula:

$$T_{surf} = T_{air} + T_{rad} \quad (5)$$

where  $T_{air}$  is air temperature,  $T_{rad}$  is equivalent temperature due to additional heating of

the pavement surface by solar radiation. The quantity  $T_{rad}$  is determined as [13]:

$$T_{rad} = \alpha \frac{I}{a_{ht}} k \tag{6}$$

where  $\alpha$  is the temperature absorption coefficient of asphalt concrete pavement that varies in the range of  $0.82 \div 0.89$  [13], for dark-colored asphalt pavement  $\alpha$  is chosen as 0.89;  $I$  ( $\text{W}/\text{m}^2$ ) is the radiation intensity, depending on the north latitude, is the total amount of direct solar radiation reaching  $1\text{m}^2$  of pavement surface in a unit time;  $k$  is coefficient of reduction of solar radiation intensity due to the presence of a lot of dust in the air, in practice for asphalt concrete pavement is often chosen in the range of  $0.5 \div 0.7$ ;  $a_{ht}$  is heat transfer coefficient, for asphalt pavement  $a_{ht} = 16 \div 20 \text{ kcal}/\text{m}^2 \cdot ^\circ\text{C} \cdot \text{h}$  ( $\sim 18.61 \div 23.26 \text{ W}/\text{m}^2 \cdot ^\circ\text{C}$ ) [13] and in this study one chooses  $a_{ht} = 18 \text{ kcal}/\text{m}^2 \cdot ^\circ\text{C} \cdot \text{h}$  ( $\sim 20.93 \text{ W}/\text{m}^2 \cdot ^\circ\text{C}$ ).

Due to time and resource limits, climate data will be collected from the database of the Federal Highway Administration of United States published free on the internet [14]. The data are surveyed over a 20-year period, from the year of 2003 to the year of 2022. The pavement surface temperatures of the average of the 7 coldest and hottest days in a year will be calculated and used as boundary conditions for the thermal analysis problem. The calculated results showed that the year with the coldest 7-day average pavement surface temperature was 2013 (henceforth called coldest case) and the year with the hottest 7-day average pavement surface temperature was 2005 (henceforth called hottest case). The results about temperature are expressed in Table 1 and Table 2 corresponding to the average temperature of 7 coldest days in the year of 2013 and 7 hottest days in the year of 2005. It can be seen that the minimum average pavement surface temperature ( $2.9^\circ\text{C}$ ) at 5 h for the coldest case and maximum ( $66.27^\circ\text{C}$ ) at 12 h for the hottest case.

Table 1. Average hourly temperatures of the 7 coldest days in 2013

No	Time (h)	$I_{\tau}^{avg}$ ( $\text{W}/\text{m}^2$ )	$T_{avg}^{air}$ ( $^\circ\text{C}$ )	$T_{avg}^{rad}$ ( $^\circ\text{C}$ )	$T_{avg}^{surf}$ ( $^\circ\text{C}$ )	No	Time (h)	$I_{\tau}^{avg}$ ( $\text{W}/\text{m}^2$ )	$T_{avg}^{air}$ ( $^\circ\text{C}$ )	$T_{avg}^{rad}$ ( $^\circ\text{C}$ )	$T_{avg}^{surf}$ ( $^\circ\text{C}$ )
1	0 h	0.00	5.71	0.00	<b>5.71</b>	13	12 h	683.99	15.23	18.90	<b>34.13</b>
2	1 h	0.00	4.83	0.00	<b>4.83</b>	14	13 h	595.46	15.60	16.46	<b>32.06</b>
3	2 h	0.00	4.13	0.00	<b>4.13</b>	15	14 h	464.73	15.57	12.84	<b>28.42</b>
4	3 h	0.00	3.56	0.00	<b>3.56</b>	16	15 h	288.91	15.06	7.99	<b>23.04</b>
5	4 h	0.00	3.14	0.00	<b>3.14</b>	17	16 h	105.63	13.50	2.92	<b>16.42</b>
6	5 h	0.00	2.90	0.00	<b>2.90</b>	18	17 h	4.11	11.59	0.11	<b>11.70</b>
7	6 h	7.27	2.76	0.20	<b>2.96</b>	19	18 h	0.00	10.89	0.00	<b>10.89</b>
8	7 h	125.43	5.23	3.47	<b>8.70</b>	20	19 h	0.00	10.29	0.00	<b>10.29</b>
9	8 h	319.09	7.94	8.82	<b>16.76</b>	21	20 h	0.00	9.64	0.00	<b>9.64</b>
10	9 h	499.94	10.77	13.82	<b>24.59</b>	22	21 h	0.00	8.93	0.00	<b>8.93</b>
11	10 h	619.31	12.97	17.12	<b>30.09</b>	23	22 h	0.00	8.10	0.00	<b>8.10</b>
12	11 h	687.01	14.34	18.99	<b>33.33</b>	24	23 h	0.00	7.09	0.00	<b>7.09</b>

Table 2. Average hourly temperatures of the 7 hottest days in 2005

No	Time (h)	$I_{\tau}^{avg}$ (W/m <sup>2</sup> )	$T_{avg}^{air}$ (°C)	$T_{avg}^{rad}$ (°C)	$T_{avg}^{surf}$ (°C)	No	Time (h)	$I_{\tau}^{ib}$ (W/m <sup>2</sup> )	$T_{avg}^{air}$ (°C)	$T_{avg}^{rad}$ (°C)	$T_{avg}^{surf}$ (°C)
1	0 h	0.00	26.1	0.00	<b>26.11</b>	13	12 h	934.99	40.8	25.84	<b>66.27</b>
2	1 h	0.00	25.7	0.00	<b>25.70</b>	14	13 h	858.26	40.7	23.72	<b>64.54</b>
3	2 h	0.00	25.4	0.00	<b>25.36</b>	15	14 h	708.90	40.0	19.59	<b>60.32</b>
4	3 h	0.00	25.1	0.00	<b>25.07</b>	16	15 h	471.90	38.6	13.04	<b>53.01</b>
5	4 h	0.00	24.8	0.00	<b>24.77</b>	17	16 h	255.20	36.0	7.05	<b>45.68</b>
6	5 h	9.34	24.6	0.26	<b>24.87</b>	18	17 h	83.30	32.8	2.30	<b>38.27</b>
7	6 h	138.21	26.5	3.82	<b>30.28</b>	19	18 h	4.16	30.9	0.11	<b>32.96</b>
8	7 h	355.24	29.2	9.82	<b>39.00</b>	20	19 h	0.00	29.5	0.00	<b>30.91</b>
9	8 h	569.57	32.9	15.74	<b>48.60</b>	21	20 h	0.00	28.5	0.00	<b>29.53</b>
10	9 h	757.60	36.1	20.94	<b>57.01</b>	22	21 h	0.00	27.8	0.00	<b>28.54</b>
11	10 h	892.80	38.2	24.68	<b>62.85</b>	23	22 h	0.00	27.3	0.00	<b>27.83</b>
12	11 h	953.43	39.6	26.35	<b>65.94</b>	24	23 h	0.00	40.8	0.00	<b>27.26</b>

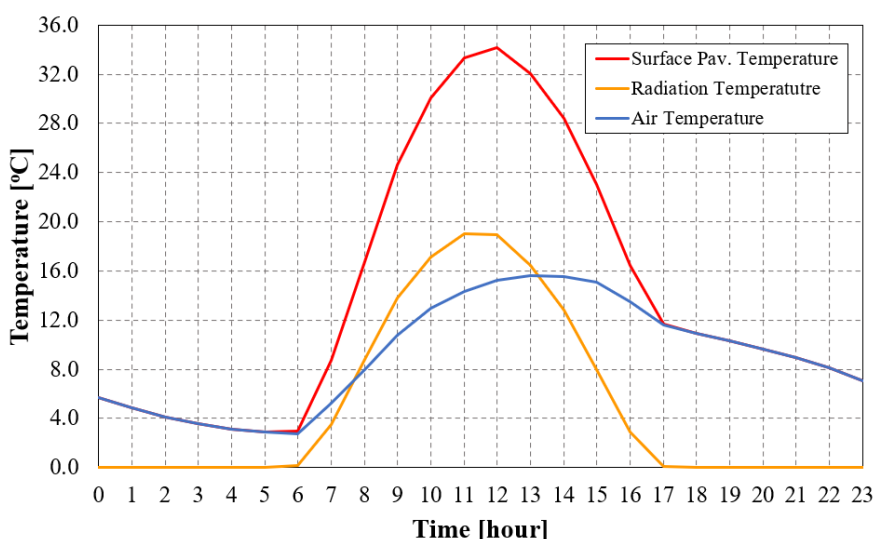


Figure 1. Average temperature variation of 7 coldest days in 2013.

Figure 1 shows the air temperature ( $T_{air}$ ), temperature due to solar radiation ( $T_{rad}$ ), and pavement surface temperature ( $T_{surf}$ ) hourly of the average of the 7 coldest days in 2013. Meanwhile, Figure 2 shows graphs of these quantities for the average of the 7 hottest days in 2005. Moreover, in Figure 2 the authors also show some field data of surface pavement temperature extracted from [15] of a typical hot day of Hanoi in 2015.

Figure 2 exhibits that the calculated maxima road surface temperature is approximately the one obtained in the field. However, the highest temperature of the road surface according to field data appears around 13 h, which is later than calculated result. It should also be recalled that, in this study, our road surface temperature calculations are based on semi-empirical theoretical formulas which do not take into account convective heat exchange.

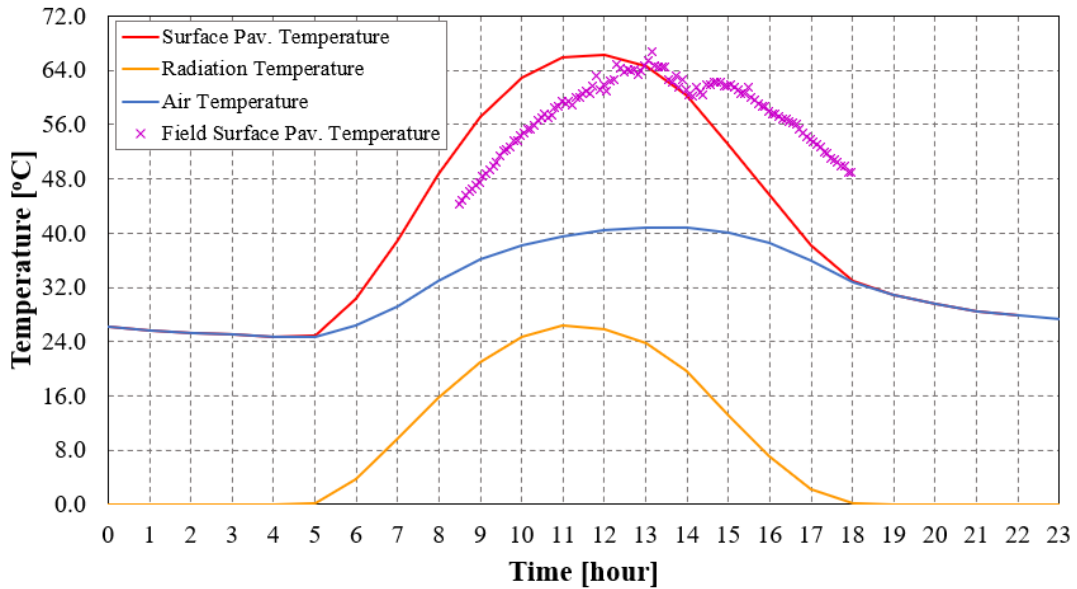


Figure 2. Average temperature variation of 7 hottest days in 2005.

It can be seen that, with both the averages of 7 coldest days and 7 hottest days, the air temperature is typically highest around 13 h - 14 h, the temperature due to solar radiation and the highest temperature of pavement surface appear between 11 h - 12 h. The lowest air temperature is usually around 4 h to 6 h. During this period, the solar radiation is equal to zero.

#### 4. Determination of temperature field in pavement structure

##### 4.1. Finite element model of the problem

In this study, the authors use the finite element method to determine the temperature distribution in the asphalt pavement. To study the temperature field in the pavement, the authors will solve a heat transfer problem in a pavement structure composed of the following layers. The top layer is asphalt concrete of 14 cm thick, the foundation is an aggregate layer of 45 cm thick and the bottom layer is compacted ground (Figure 3). The calculated parameters are given in the Table 3 below [2, 16].

Table 3. Calculation parameters of the structure

Layer	Thickness $h$ (cm)	Thermal conductivity $\lambda$ (J/m.h.°C)	Specific heat $C_p$ (J/kg.°C)	Unit weight $\rho$ (kg/m <sup>3</sup> )
Asphalt concrete	14	1.8	1000	2400
Aggregate base	45	1.7	850	2200
Subgrade		1.5	850	2000

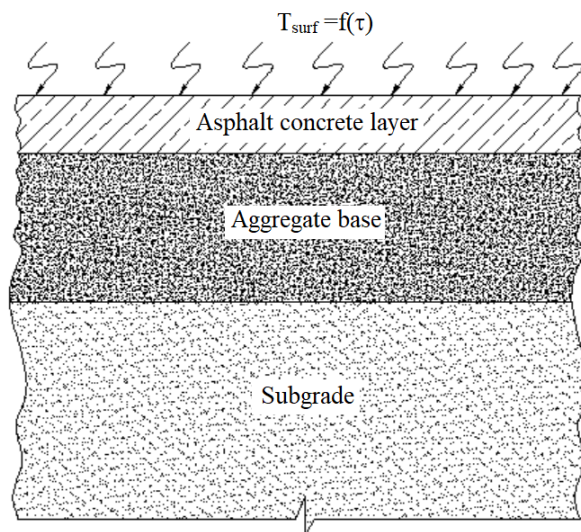


Figure 3. Asphalt concrete pavement structure in the study.

Since the environment temperature acts uniformly on the entire surface of the pavement, the heat transfer problem in the pavement structure can be solved as a one-dimensional one. However, in order to show more clearly the temperature field in the structure, the authors address the problem based on a two-dimensional model of axial symmetry with a radius of 1 m. This does not change the nature of the problem in the study. The axially symmetrical 2-D geometry model is illustrated in Figure 4.

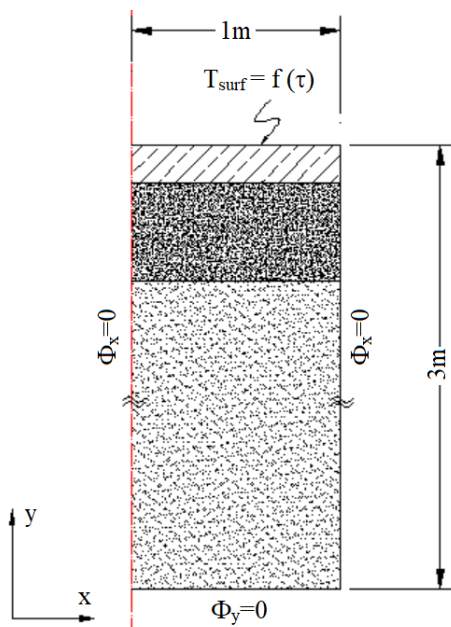


Figure 4. Geometry model and boundary conditions of the problem.

Relating to finite elements of the model, four-node rectangular elements are chosen and the model is discretized into 1228 elements. The numerical simulation is performed on the open source finite element code ASTER.

The boundary conditions of the problem are imposed as follows:

- The surface pavement temperature is imposed according to Table 1 and Table 2 with the temperature over time.

- At the bottom edge of the model, the normal heat flow is equal to zero ( $\Phi_y = 0$ ). In this study, the depth of the model is limited to 3 m including the asphalt concrete layer, the foundation layer and the subgrade layer. This is based on the notion that, at this depth no heat transfer takes place to the underlying soil layer.

- Because of the use of the 2-D axial symmetric model, on the lateral edges of the model the normal heat flow is equal to zero ( $\Phi_x = 0$ ).

In fact, the temperature of the soil is affected by geothermal phenomena, i.e., the heat transferred from the earth's core. In a small depth of study, one can consider that the temperature of soil layer is mainly caused by the heating of the sun. Therefore, relating to the initial condition of the problem, one imposes the initial temperature of the system being equal to the lowest temperature of the pavement surface (at 5 h for the coldest case and at 4 h for hottest case), i.e., 2.9°C and 24.77°C, respectively. With regard to this initial condition, when the temperature is applied to the pavement surface, due to the temperature difference, the heat will flow into the pavement structure system. Heat exchange will always take place in the material layers. The temperature load is imposed on the system surface in a certain number of day-night cycles. The number of cycles will be determined by the condition that, when the temperature distribution over time in a day-night cycle reaches steady state then the calculation will be stopped.

#### **4.2. Result of temperature field in the pavement**

Figure 5 shows the temperature in depth at time  $\tau = 5$  h of 10 day-night cycles for the coldest case. As can be seen, the temperature difference between the top and bottom of the asphalt concrete layer increases gradually from the first cycle to the following cycles. The reason for this instability is that the initial temperature of the system is lower than the excitation temperature, the system will absorb heat from the surface. After such a number of repeated day-night cycles, the law of thermal evolution in the system will no longer depend on the initial temperature of the system, but only on the excitation temperature on the surface. The results showed that, up to the 10<sup>th</sup> cycle, the temperature distribution in depth is almost unchanged at each instant. Thus, the results of this cycle will be used in the later analysis of the article.

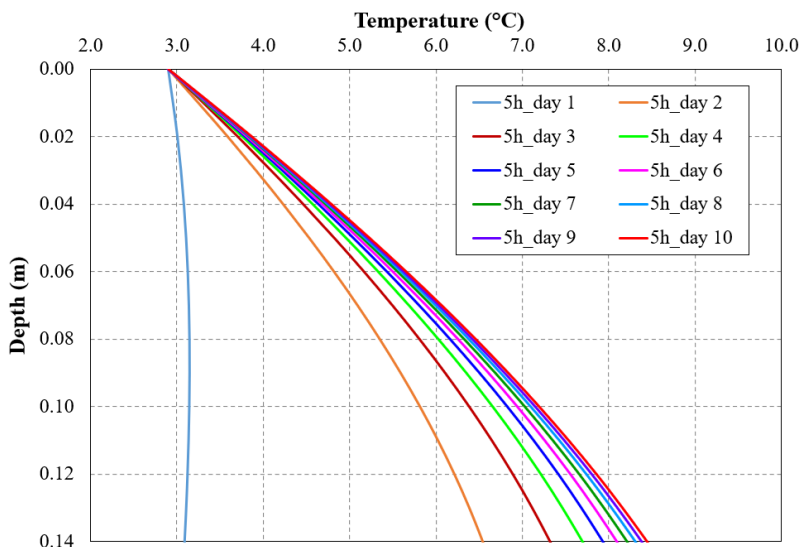


Figure 5. Temperature distribution in asphalt concrete layer in depth at 5 h of 10 day-night cycles.

Figure 6 and Figure 7 show the variation of temperature in depth from 1 h to 24 h of the day over a depth of 3.0 m for the coldest case and the hottest case, respectively. It can be observed that at a depth of 2.5 m, the temperature of the system is almost unchanged with time and approximates the initial temperature. This suggests that at this depth, heat transfer no longer occurs.

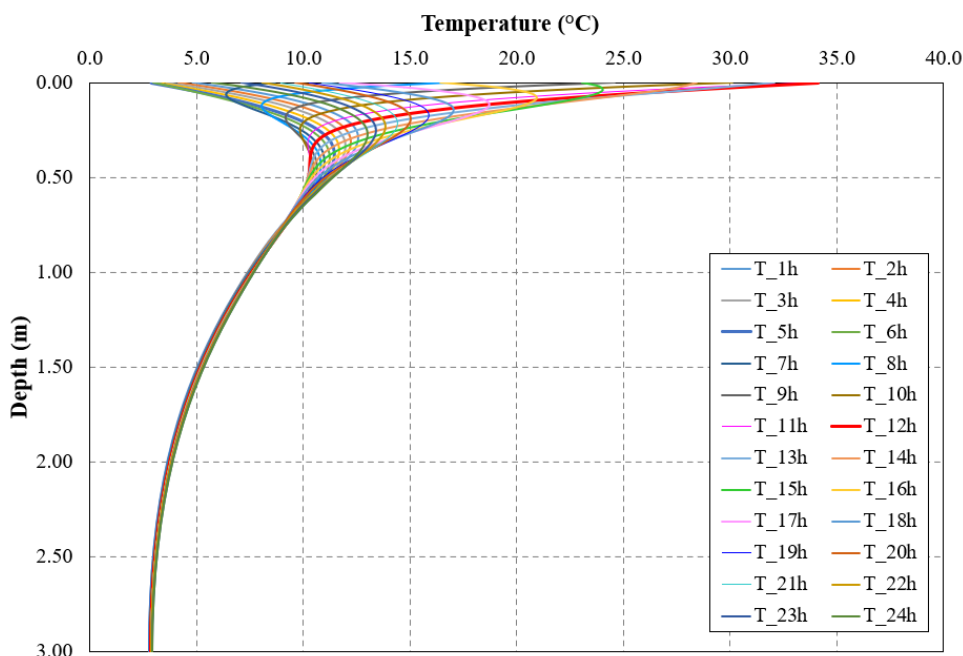


Figure 6. Temperature distribution in depth in the pavement-roadbed for the coldest case.

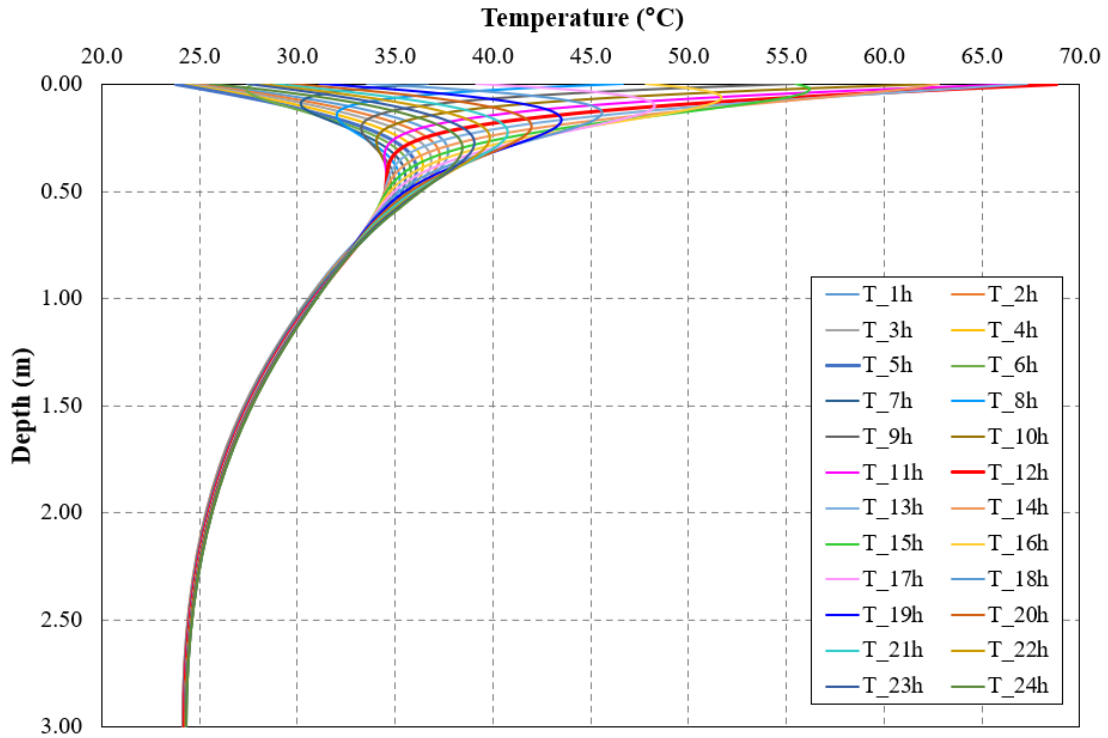


Figure 7. Temperature distribution in depth in the pavement-roadbed for the hottest case.

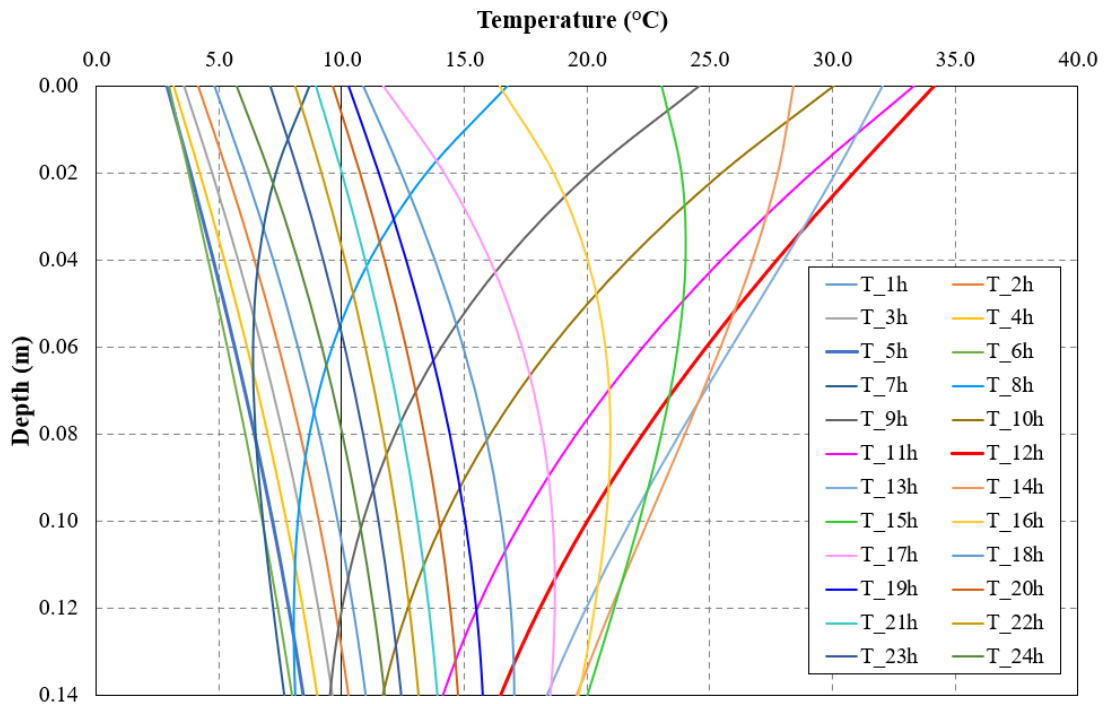


Figure 8. Temperature distribution in depth in the asphalt concrete layer for the coldest case.

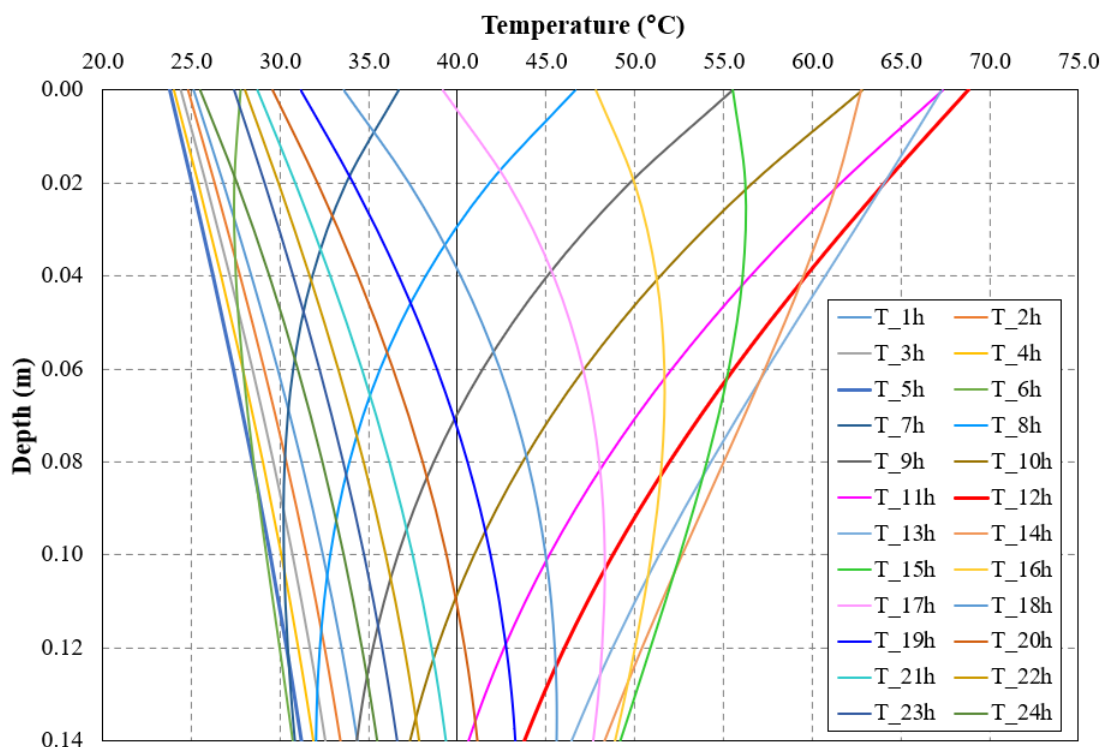


Figure 9. Temperature distribution in depth in the asphalt concrete layer for the hottest case.

Figure 8 and Figure 9 are graphs of the temperature distribution with depth within the asphalt concrete layer. It can be seen that at the bottom of the asphalt layer, the temperature changes over time from 1 h to 24 h because at this location the heat is continuously exchanged between the asphalt layer and the underlying foundation.

It is observed from Figure 8 and Figure 9 that in a day-night cycle, between 7 h and 15 h the temperature in the asphalt concrete layer gradually decreases from the pavement surface to the bottom of the layer. This is the period that the pavement surface is heated by solar radiation and air temperature. The higher temperature on the surface will be transferred to the lower temperature area. The maximum temperature of the surface reaches at 12 h. From about 13 h, the surface temperature starts to decrease while the one at the bottom gradually increases. In this time, the heat accumulated in the previous stage induces the zone around the bottom of the asphalt layer having higher temperature than the one of the surface where the temperature drops. Thus, the heat transfer process occurs in the opposite direction, i.e. from the bottom of the asphalt layer to the top of the pavement. This process is heat dissipation of the pavement. The biggest temperature difference in this period is at 18 h.

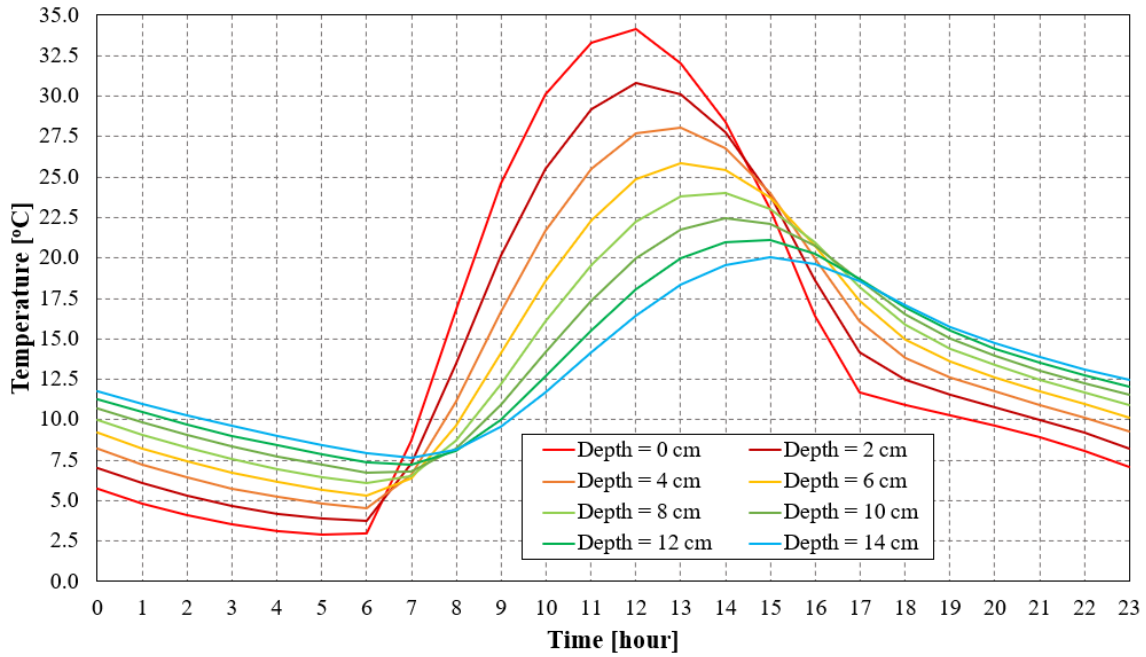


Figure 10. Temperature evolutions at different depths in the asphalt layer for the coldest case.

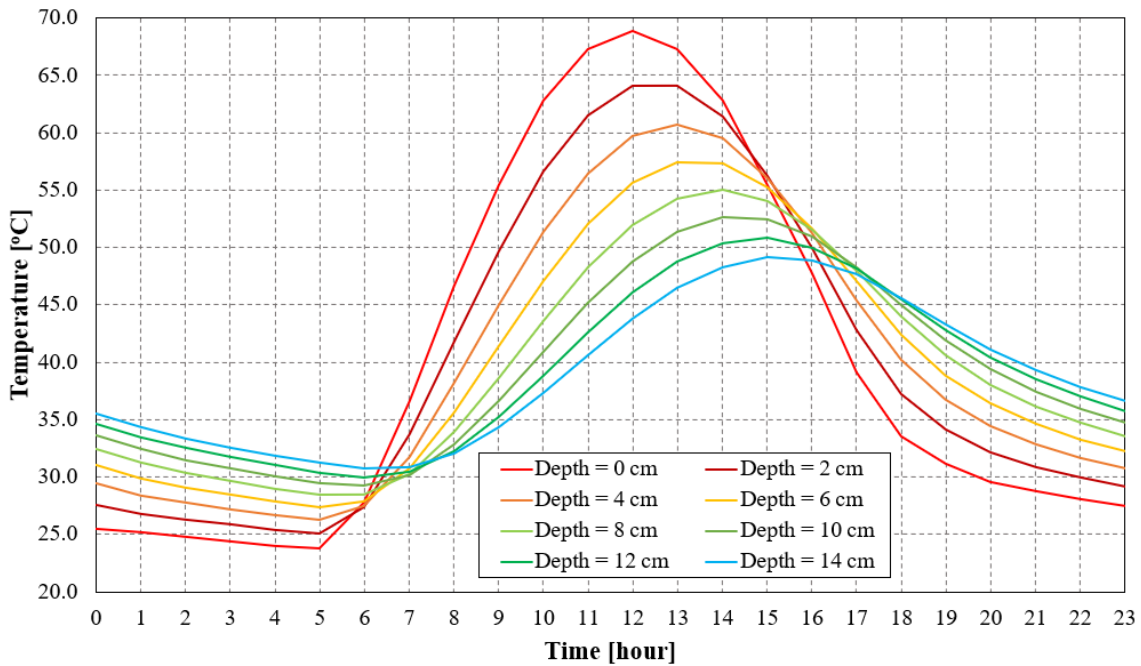


Figure 11. Temperature evolutions at different depths in the asphalt layer for the hottest case.

Figure 10 and Figure 11 show that the temperature evolutions at different depths in the asphalt layer for the two case studies, respectively. The progression of temperature at different depths of the pavement for two cases have the same tendencies.

In the coldest case, it can be observed from Figure 10 that the greater depth, the higher

minima temperature and the later time of the minima temperature reached. Concretely, the minima temperatures of the points at depths of 0, 2, 4, 6 and 8 cm reach at 6h while they reach at 7 h for the points at depths of 10, 12 and 14 cm. With respect to the hottest case, the greater depth of the point, the lower maxima temperature reached (Figure 11). Precisely, the road surface temperature and at 2 cm depth peak at 12 h, at depths of 4 and 6 cm the maxima temperature reaches at 13 h, at depths of 8 and 10 cm this time is at 14 h while at depths of 12 and 14 cm the maxima temperature reaches at 15 h. This shows that over the depth the time to reach the maxima temperature of the asphalt concrete has also a certain delay. The time delay of the minima and maxima temperatures of the asphalt concrete with depth is because of the process of heat transfer from higher temperature to lower temperature zones.

According to some authors [17-19], with respect to asphalt concrete pavement, working temperature above 40°C is considered unfavorable because the strength of the asphalt concrete is quite low and the pavement surface may appear plastic deformation. Besides, when the temperature is below 10°C, the asphalt concrete is brittle and prone to cracking under the effect of loading [15]. It can be seen in Figure 8 that in the period from 0 h to 7 h the asphalt layer has a temperature below 10°C. Figure 9 shows that in the time between 10 h and 17 h, the temperature of the asphalt layer is greater than 40°C. Based on these characteristics, it is possible to take measures to limit heavy trucks running on the road during the above time frame to minimize the destructive effect of the load on the pavement.

It should also be noted that, the flexible pavement calculation standard of Vietnam stipulates that the temperature for calculating tensile-bending stress in the asphalt concrete is 10°C - 15°C and the temperature for calculating shear stress in asphalt concrete layer is 60°C [20]. The lowest and highest temperature values of asphalt concrete received in the above estimations are outside these limit temperature values.

## **5. Conclusions**

The focus of the article is on predicting the temperature distribution in asphalt concrete pavement in the Hanoi region. Climate data were collected from the free database of the Federal Highway Administration of the United States, which was used to calculate the pavement surface temperature. This temperature is a boundary condition of the heat transfer problem of the pavement structure. When field measurement data are not available, this database can be used to determine the asphalt pavement temperature in Vietnam.

The calculation results showed that the temperature of the pavement surface increases gradually from about 5 a.m., peaks around 12 p.m., and then gradually decreases from 1 p.m. to 12 p.m.

The problem of heat transfer in the pavement structure was solved using the finite element method. The finite element method proved to be effective in studying the thermal state of the asphalt pavement. The solution of the problem showed that the heat on the road surface is transmitted down into the pavement structure to a maximum depth of 3 meters. However, at a depth of about 2.5 meters, the temperature corresponding to the time of day does not change significantly and the heat transfer no longer occurs at this depth.

The asphalt pavement has a relatively low temperature during the period from 0 a.m. to 6 a.m., and thereby the material exhibits brittleness. In contrast, the period from 10 a.m. to 4 p.m. is the time that the asphalt layer has a high temperature, at which the strength and deformation resistance of the material are relatively low. These are the times when heavy vehicles should be restricted to minimize the destructive effects of vehicle loads. Furthermore, the results of this study can be used to determine the calculated temperature in asphalt pavement calculation.

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## DỰ BÁO SỰ PHÂN BỐ NHIỆT ĐỘ TRONG MẶT ĐƯỜNG BÊ TÔNG NHỰA KHU VỰC HÀ NỘI BẰNG MÔ PHỎNG SỐ

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**Tóm tắt:** Bài báo trình bày việc xác định phân bố nhiệt độ trong mặt đường bê tông nhựa khu vực Hà Nội dựa trên mô phỏng số bằng phương pháp phần tử hữu hạn. Các dữ liệu khí hậu được thu thập từ dữ liệu trực tuyến miễn phí của Cục Quản lý đường bộ Hoa Kỳ. Từ các dữ liệu về khí hậu, nhiệt độ bề mặt của mặt đường được tính toán để làm điều kiện biên cho bài toán truyền nhiệt của mặt đường. Kết quả tính toán cho thấy, nhiệt độ bề mặt đường thường cao nhất vào khoảng 11 - 12 giờ trưa trong khi nhiệt độ thấp nhất thường vào khoảng 4 - 6 giờ sáng. Nhiệt độ bên trong lớp mặt đường thường cao vào khoảng thời gian từ 10 giờ sáng đến 16 giờ chiều, lúc này cường độ và khả năng chống biến dạng của mặt đường tương đối thấp. Ngược lại, nhiệt độ bên trong mặt đường thấp trong khoảng thời gian từ 0 giờ đến 6 giờ sáng, đây là lúc bê tông nhựa thể hiện tính giòn và dễ bị nứt. Kết quả phân tích sự phân bố nhiệt độ trong kết cấu mặt đường có thể được dùng cho việc tính toán thiết kế mặt đường cũng như trong dự báo hằn lún vết bánh xe.

**Từ khóa:** Mặt đường bê tông nhựa; nhiệt độ bề mặt đường; phân bố nhiệt độ; phương pháp phần tử hữu hạn.

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