A Study of Unsteady Variations of Highway Temperatures in Winter and Summer

X. Cao, B. Song, W. Hamada, H. Maeda, and T. Nakayama

Abstract — The unsteady variations of temperatures of highways in four places are investigated in this study. A physical model is built based on heat transfer, and the computer program for the analysis is generated by authors in Fortran code. The effects of solar radiation, air temperature, wind velocity and location on highway temperature are analyzed. The results show that the highest temperature on the highway surface could be over 60 °C in summer, and the lowest temperature could be below -14 °C in winter. The solar radiation, air temperature, location and wind velocity affect the road temperature obviously. Due to the thermal inertia, with the increase in depth, the temperature changes more slowly and weakly. At the depth of about 0.5 m below surface, the variation of road temperature is not over 1 °C. The structure and the altitude above sea level of the highway also play important roles in influencing road temperature. The frozen depths for the researched highways could reach 0.25 m–0.95 m.

Keywords — highway, numerical simulation, solar radiation, temperature, winter.

I. INTRODUCTION

Highway makes traffic convenient. The Aokijima section on National Highway 18 is one of the busiest highway sections in Nagano prefecture, Japan. Its traffic volume reaches about mean 46900 vehicles every 12 hours. The highway bears heavy traffic loads every day and experiences the solar radiation, snow, rain, frost, wind and temperature change, which will result in the road surface deforming and cracking [1], [2] so that the traffic accidents might be caused. The heat wave occurred in the summer, 2015 in India resulted in the pavement of a road section near a hospital in New Delhi being melted then the zebra crossing deformed [3]. The freezing of the road surface in Fort Worth, Texas on Feb. 12, 2021 led to more than 100 vehicles colliding (seen in Fig. 1), which caused at least 5 dead and 36 injured [4]. The extraordinarily high and low temperatures of highway are easy to cause the road surface deformation or crack, and then affect traffic safety. Cao et al. investigated the thermal performance of the bridge roadway [5]. Bai experimentally analyzed the characteristic of heat transfer for asphalt pavement [6]. A physical model is established in this study, and a Fortran program is written to simulate the unsteady variations of highway temperatures. The four locations of National Highways 18, 19 and 20 in Nagano prefecture, Japan, which are Aokijima in Nagano city (Highway 18), Hirataminami in Matsumoto (Highway 19), Saku in Karuiuzawa (Highway 18) and Motomati in Suwa (Highway 20), are adopted in this analysis. To investigate the highest and the lowest temperatures in the highways, the actually observed weather data respectively in summer and winter are used in the analysis.

II. PHYSICAL MODEL

Based on the principle of heat transfer, a physical model and its boundary conditions are established. The governing equation is [7]:

\[ \rho C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} (k \frac{\partial T}{\partial x}) \]  

(1)

where \( T \) [K] is temperature of highway, \( x \) [m] is coordinate in the direction of road depth, \( t \) [s] is time, \( \rho \) [kg/m\(^3\)] is density, \( C_p \) [J/(kgK)] is specific heat, and \( k \) [W/mK] is thermal conductivity.

Boundary conditions at road surface are expressed as [8], [9]:

\[ k \frac{\partial T}{\partial x} = q_{\text{sun}} - q_{\text{conv}} - q_{\text{emit}} \]  

(2)

\[ q_{\text{sun}} = \alpha q_{\text{solar}} \]  

(3)

\[ q_{\text{conv}} = h(T_s - T_{\text{air}}) \]  

(4)

\[ q_{\text{emit}} = \varepsilon T_s^{4} - T_{\text{sky}}^{4} \]  

(5)

W. Hamada, Faculty of Engineering, Shinshu University, Japan.
H. Maeda, Japan Bridge & Structure Institute, Inc., Japan.
T. Nakayama, Faculty of Engineering, Shinshu University, Japan.
where, $\alpha$ and $\varepsilon$ are effective solar absorptivity and emissivity, respectively, $q_{\text{solar}}$ [W/m²] is solar radiation rate on road surface, $T_s$ [K] is the temperature in highway surface, $T_{\text{air}}$ [K] is air temperature, $T_{\text{sky}}$ [K] is sky temperature and its relation with $T_{\text{air}}$ can be expressed as [10]

$$T_{\text{sky}} = 0.0552T_{\text{air}}^2$$

(6)

The parameter $\sigma$ is Stefan-Boltzmann constant, which is equal to $5.669 \times 10^{-8}$ [W/m²·K⁴]. The parameter $h$ [W/m²·K] in Eq. (4) is heat transfer coefficient and can be expressed by Eqs. (7)-(9) [11].

$$h^3 = h_{\text{nat}}^3 + h_{\text{for}}^3$$

(7)

$$h_{\text{nat}} = \begin{cases} \frac{k_{\text{air}}}{L} 0.54Ra^{0.25} & \text{for } 2 \times 10^4 < Ra \leq 8 \times 10^6 \text{ and } T_s \geq T_{\text{air}} \\ \frac{k_{\text{air}}}{L} 0.15Ra^{1/3} & \text{for } 8 \times 10^6 < Ra < 10^{11} \text{ and } T_s \geq T_{\text{air}} \\ \frac{k_{\text{air}}}{L} 0.27Ra^{0.25} & \text{for } 10^5 < Ra < 10^{10} \text{ and } T_s < T_{\text{air}} \end{cases}$$

(8)

$$h_{\text{for}} = \begin{cases} 0.664 \frac{k_{\text{air}}}{L} Re^{0.5}Pr^{1/3} & \text{for } Re \leq 5 \times 10^5 \\ \frac{k_{\text{air}}}{L} (0.0365Re^{0.8} - 853)Pr^{1/3} & \text{for } Re > 5 \times 10^5 \end{cases}$$

(9)

where $k_{\text{air}}$ [W/mK] is thermal conductivity of air, $Ra$ is Rayleigh number, $L$ [m] is width of highway, $Pr$ is Prandtl number, $Re$ is Reynolds number and its relation to wind velocity $u$ [m/s] is given in Eq. (10):

$$Re = \frac{uL}{v_{\text{air}}}$$

(10)

where $v_{\text{air}}$ [m²/s] is air kinematic viscosity. At the depth of 2 m from the road surface, a given temperature is adopted as the boundary condition, which is 10 °C for winter and 20 °C for summer. The initial temperature distribution is obtained through linear interpolation.

In the analysis, the explicit finite difference method is applied. The computer program for the analysis is generated by authors in Fortran code.

III. THE STRUCTURE OF ROAD PROFILE AND THE THERMAL PROPERTIES OF MATERIALS

The profile of the highway is commonly divided as six or seven layers. The materials of each layer and their thermal properties are summed up respectively in Table I-IV. The meaning of each layer material is represented in the abbreviation format as shown in the tables and explained below.

- porous asphalt-concrete type I → PACTH
- coarse-grain asphalt-concrete improved polymer type II → CGACIPTII
- recycled big-diameter grain mixture → RBDGM
- recycled crushed stone → RCS
- crushed stone → CS
- dense-graded asphalt-concrete improved polymer type II → DGACIPTII
- recycled coarse-grain asphalt-concrete → RCGAC
- recycled heat-treated asphalt stabilization → RHTAS

Each layer normally consists of several different raw materials. Its effective thermal property is calculated [12] by:

$$\lambda_{\text{ef}} = \sum_{i=1}^{n} \alpha_i \lambda_i$$

(11)

where $\lambda_i$ is the thermal property of material $i$, and $\alpha_i$ is the mass fraction of material $i$ in the layer. The Materials for each layer and their thermal properties are filled in Tables I-IV.

| TABLE I: THE MATERIALS FOR EACH LAYER AND THEIR THERMAL PROPERTIES OF KARUIZAWA HIGHWAY |
|--------------------------------------------|
| Materials for each layer | Thickness [mm] | Density [kg/m³] | Specific heat [J/kg K] | Thermal conductivity [W/m K] | Solar absorptivity |
|--------------------------|----------------|----------------|---------------------|----------------------------|------------------|
| PACTH                    | 50             | 2056           | 1214.9              | 1.392                      | 0.9013           |
| CGACIPTII                | 50             | 2378           | 1185.7              | 1.566                      | -                |
| RBDGM                    | 200            | 2401           | 1150.3              | 1.296                      | -                |
| RCS                      | 300            | 3111           | 1127.2              | 1.350                      | -                |
| CS                        | 300            | 2644           | 1213.4              | 1.500                      | -                |
| sand                     | 1100           | 3940           | 920.0               | 1.070                      | -                |

| TABLE II: THE LAYER MATERIALS AND THEIR THERMAL PROPERTIES OF NAGANO HIGHWAY |
|--------------------------------------------|
| Materials for each layer | Thickness [mm] | Density [kg/m³] | Specific heat [J/kg K] | Thermal conductivity [W/m K] | Solar absorptivity |
|--------------------------|----------------|----------------|---------------------|----------------------------|------------------|
| DGACIPTII                | 50             | 2384           | 1145.1              | 1.414                      | 0.8974           |
| CGACIPTII                | 50             | 2378           | 1185.7              | 1.566                      | -                |
| RCGAC                    | 50             | 2379           | 1150.3              | 1.324                      | -                |
| RHTAS                    | 80             | 2378           | 1090.7              | 1.160                      | -                |
| CS                        | 150            | 2644           | 1213.4              | 1.500                      | -                |
| RCS                      | 150            | 3111           | 1127.2              | 1.350                      | -                |
| sand                     | 1470           | 3940           | 920.0               | 1.070                      | -                |
The temperature changes normally occur in the first layer and second layer from road surface. Therefore, their thermal properties are very important. From the tables, there are no obvious difference in the two layers, especially between the first layers of different roads. The solar absorptivity and material emissivity are treated as the same value and is equal to about 0.9.

The air thermal properties, except that the specific heat of air \( C_{\text{air}} \) is treated as a constant of 1006 [J/kgK], could be expressed as functions of air temperature [13]. The dynamic viscosity could be:

\[
\mu_{\text{air}} = \frac{1.458 \times 10^{-6} \rho_{\text{air}}^{\frac{3}{2}}}{110.4 + T_{\text{air}}}
\] (12)

The thermal conductivity \( k_{\text{air}} \) can be expressed as:

\[
k_{\text{air}} = \frac{2.6482 \times 10^{-3} \rho_{\text{air}}^{\frac{3}{2}}}{T_{\text{air}} + 245.4 \times 10^6}
\] (13)

The density \( \rho_{\text{air}} \) is:

\[
\rho_{\text{air}} = \frac{\rho_{\text{air}}}{R_{\text{air}}}
\] (14)

where \( \rho_{\text{air}} \) [Pa] is atmosphere pressure, and \( R \) is equal to 287 [J/kgK], an air constant.

### IV. Winter and Summer Meteorological Data Adopted for this Research

To investigate the highest temperature and the lowest temperature of the highways, the winter and the summer meteorological data were adopted that are the measured data in four locations [14]. The meteorological data of January 13, 2013 and July 26, 2014 in Nagano are adopted. The data of January 14, 2009 and July 26, 2014 in Matsumoto are adopted. The data of December 20, 2012 and August 11, 2013 in Karuizawa are adopted. The data of February 2, 2011 and July 17, 2011 in Suwa are adopted.

Based on the adopted meteorological data, the functions of outdoor air temperature \( T_{\text{air}}(t) \), solar radiation \( q_{\text{sol}}(t) \) and wind velocity \( u(t) \) are obtained with an interpolation method in our Fortran computation program. The variations of air temperature, solar radiation and wind velocity with local time are plotted in Fig. 2-4. In Fig. 2, S is the abbreviation of summer, and W is the abbreviation of winter.

![Fig. 2 Solar radiation history in winter and summer for four locations.](image)

![Fig. 3 Variations of air temperature with local time in winter for four locations.](image)
From Fig. 2, it can be seen that the solar radiation in summer is much higher than that in winter. The highest values in summer were in the range from 824 to 947 W/m² for different locations. However, the highest values in winter were only in the range of 500 to 627 W/m². The irradiation time in winter decreases to 7 hours from 13 hours in summer. Because it is only 70 km from Nagano to Matsumoto, and the weather data in summer were adopted in the same day (July 26, 2014), the solar radiation data are the same. From Fig. 3, the lowest air temperatures in winter are at about 7 o’clock, and the highest air temperature is at around 13 o’clock. It can be seen from Fig. 4 that the windy time is between 10 to 21 o’clock.

V. RESULTS AND DISCUSSION

Utilizing the generated Fortran program, the temperatures of highway are obtained. The variations of temperature at different depths of highway in Karuizawa with time in winter are given in Fig. 5. The Figure shows that the road surface temperature changes markedly. At 7 o’clock, it drops to it’s the lowest value of -14.5 °C, and at 13:20, it reaches it’s the highest value of 10.6 °C. With the depth increasing, the magnitude of the temperature weakens down, and the time to reach its maximum value is delayed. At the depth of 0.5 m, the temperature almost unchanged. The figure also shows that for the thickness from 0.1 m to 0.5 m, the pavement always keeps at frozen state, which might cause traffic accident.

The effects of wind velocity on temperatures for different depths of highway in Matsumoto in winter are shown in Fig. 6. From Fig. 6, it can be seen that the effect of wind velocity on road surface temperature is not obvious. The radiation reaches its maximum value of 500 W/m² at 12 o’clock. The road surface temperature and air temperature reach their maximum values at about 13:30 due to thermal inertia. The effects of weather parameters on road surface temperature are normally from the influence of solar radiation. With the increasing in solar radiation, the air temperature, road surface temperature and wind velocity increase, and then the road surface temperature is affected furthermore.

The effects of radiation, air temperature and wind velocity on road surface temperature at Nagano in winter are plotted in Fig. 7. The figure shows that the effect of wind velocity on road surface temperature is not obvious. The radiation reaches its maximum value of 500 W/m² at 12 o’clock. The road surface temperature and air temperature reach their maximum values at about 13:30 due to thermal inertia. The effects of weather parameters on road surface temperature are normally from the influence of solar radiation. With the increasing in solar radiation, the air temperature, road surface temperature and wind velocity increase, and then the road surface temperature is affected furthermore.

The variations of road surface temperature with local time in summer for four locations are plotted in Fig. 8. The figure shows that the road surface highest temperatures reach a range of 55 °C to 60 °C. From 10 o’clock to 18 o’clock, the road surface temperatures keep at higher value over 45 °C. The difference of the road surface temperatures can be attributed to its latitude, weather condition and altitude. The altitude of Karuizawa is about 1000 m above sea level while the altitude of Nagano is only 350 m above sea level so that the road surface temperature in Nagano is 5 °C higher than that in Karuizawa.
The variations of pavement temperatures at 0.5 m depth from road surface with time in winter for different locations are plotted in Fig. 10. From the figure, it can be seen that the temperature changes for all locations are not more than 1 °C in 24 hours, which means that the temperature changes mainly occur in 0.5 m pavement in Nagano prefecture.

The variations of road temperatures with depth at 7 o’clock in winter for different locations are plotted in Fig. 11. The figure reveals that the frozen depths for four locations are quite different. In Karuizawa, the frozen depth could be 0.95 m, while in Nagano, the frozen depth is only 0.25 m. The calculated data also show that the lowest surface temperature normally occurs in 7 o’clock in winter, and maximum difference between the road surface temperature and the interior temperature (0.5m depth) happens at 14 o’clock. The result could be a useful reference for highway design and the material selection. At high humidity, or in a snow and rain weather, it might be frozen on road surface in winter, which is dangerous for vehicles.
VI. CONCLUSIONS

Through analyzing the above results, the conclusions can be drawn as follows:

(1) The highest road surface temperatures in summer for the investigated highways can reach 55~60 °C, and they keep over 45 °C for 8 hours.

(2) The lowest surface temperatures in winter for the investigated highways might drop to -7~-14.5 °C at 7 o’clock, and from 21 o’clock to next day 9:30, the road surface temperatures for all locations are below 0 °C in winter.

(3) The main effect on highway temperature comes from solar radiation. The air temperature, wind velocity, and location altitude and latitude also play roles in influencing highway temperatures. The increases in altitude and wind velocity commonly cause a decrease in highway temperature.

(4) With the increase in depth, the changes of pavement temperature weaken down and will be delayed. At the depth of about 0.5 m below surface, the variation of road temperature is not over 1 °C.

(5) The frozen depths for the researched highways could be 0.25 m~0.95 m.

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