Temperature Gradient of RCC-AC Composite Pavements

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Abstract: In this paper, the temperature gradient of a composite pavement structure – asphalt pavement on top of roller compacted portland cement concrete pavement (RCC-AC) is studied based on the thermo-conductivity theory. The temperature yearly variation is approximately expressed with the temperature variation coefficient and the yearly average maximum and minimum temperature of the ground (pavement surface). The temperature daily variation is described with the daily maximum/minimum temperature effect coefficient. Based upon the boundary conditions of the composite pavement structure, the analytical solution of the temperature gradient of the composite pavement is given, and the method of weighted residuals (MWR) on solid mechanics and the principle of heat transfer are used in the study. The effect of both yearly and daily temperature variance on the temperature gradient of composite pavement is investigated.

Keywords: temperature gradient, composite pavement, thermo-conductivity theory, method of weighted residuals

1. Introduction

The effect of air temperature on pavement structures has become as an important issue. Many other researchers have studied the pavement temperature gradient for concrete and asphalt pavement. Empirical correlations were generated such as those found in the work done by Geiger (1959) and Vehrencamp (1953). Barber (1957) reported the Calculation of Maximum Pavement Temperatures from weather data based upon the observation of the Arlington Road Test. The weather data such as wind speed, precipitation, air temperature, and solar radiation were used to compute the temperature distribution (surface and 3.5 inch or 8.9 cm below the surface). The observed pavement temperature fluctuations were similar to a sine curve with a period of one day. Straub et al. (1968) investigated a 6-inch and a 12-inch thick pavement. They found that the model provided a good correlation between measured temperatures and those predicted. Demsey and Thompson (1970) evaluated the pavement temperatures by evaluating frost action in multilayered pavements. Later, Dempsey et al (1987) characterized the temperature effects for pavement analysis and design and developed a climatic database in Illinois. In addition, contributions in this area also include the work don by Rumney and Jimenez (1971), Williamson (1972), Schenk, Jr. (1963), Christison and Anderson (1972), Noss (1973), Southgate and Deen (1969), Berg (1974), Wilson (1975), Emerson (1968), Spall (1982), Highter and Wall (1984), Carmichael et al (1977), Wolfe et al (1987), and Hsieh et al (1989).In the Superpave study, the Superpave binder specification was based directly on the climate in which the pavement will serve providing a realistic correlation between climatic conditions at a given location and pavement performance. The high pavement design temperature was found at a depth of about 20mm (0.8 inches) below the pavement surface, and the low pavement design temperature was found at the surface of the pavement. The pavement temperature is a function of the latitude of the location, the air temperature, and the depth to surface.

However, many researchers only considered the daily variation of temperature in the solution of temperature gradient, while the yearly variation is not considered. In this paper, the temperature gradient of a composite pavement structure – asphalt pavement on top of the roller compacted portland cement concrete pavement (RCC-AC) is studied.

2. Equation of Heat Conductivity in Layered Pavement System

Generally, the effects from ambient environment on pavements in the specific regions could be investigated based on assumption that the region is a two dimensional (2D) plane field with non-steady temperature. Based on this assumption, the problem can be simplified further by neglecting the temperature variation along the transverse direction of the pavements, as shown in Fig 1. In Fig 1, the x-coordinate axis is along the driving direction of pavement (longitudinal direction), y-coordinate is the transverse direction and z-coordinate is along the depth direction, as shown in the figure. Then, the problem is transformed into a non-steady temperature problem in one-dimensional continuous three-layer system and can be expressed by the following differential Equation (1) according to the therom-conductivity theory.

$$\frac{\partial T_j(t,z)}{\partial t} - \theta_j \frac{\partial^2 T_j(t,z)}{\partial z^2} = 0 \quad (j=1,\,2,\,3) \tag{1}$$

where, $T_j(t \cdot z)$ and θ_j are the temperature field functions in different layers (unit is °C) and the thermo-conductivity coefficient of different layers in pavement(unit is m^2/h), respectively.

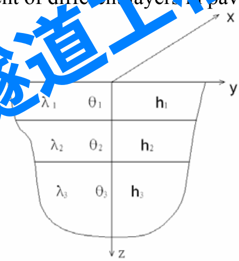


Fig 1. Pavement structure for asphalt overlay on the RCC

3. Ambient Temperature and Solar Radiation

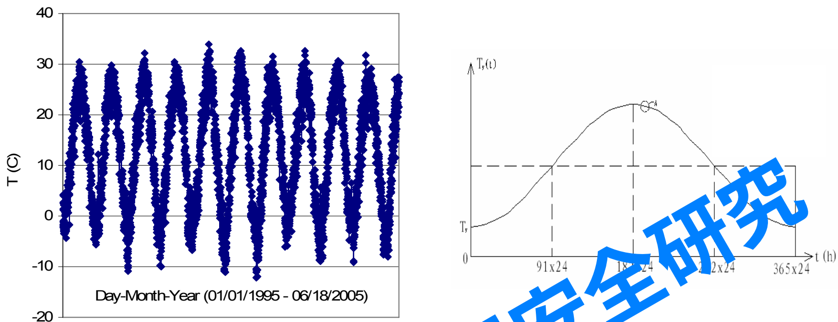
3.1 Ambient Temperature

The daily periodic temperature variation as well as the yearly periodic temperature variation determines the varying magnitude of atmospheric temperature which affects the temperature field. For example, although daily temperature changes periodically, the temperatures in summer are higher than those in winter (in the U.S. and China). Fig 2 shows this phenomenon. In order to illustrate the yearly variation of the temperature, the daily temperatures in Beijing from 1995 to 2005 were shown in Fig. 2a. Even though the low and high temperatures of each year are not exactly the same, the temperature data show a sine function across the days with 12 month as a period. Therefore, in the study of the pavement temperature field, it is insufficient to consider the daily variation of temperature but neglect the yearly variation. Based upon the weather data, the annual temperature variation can be simulated using the sine function approximately. As shown in Fig. 2b, the function can be written as follows:

$$T_y(t,z) = [T_y + \widetilde{T}_y \sin(\omega(t - 365 \times 6))]e^{-\alpha_1 z} \tag{2}$$

$$T_y = \frac{1}{2}(T_y^{\max} + T_y^{\min}),\ \widetilde{T}_y = \frac{1}{2}(T_y^{\max} - T_y^{\min}) \tag{3}$$

where, $\omega = 2\pi/(365 \times 24)$; α_1 is ambient variation coefficient departing from the pavement surface along vertical coordinate system, which is obtained by measurement. $T_d^{\max}$ and $T_d^{\min}$ are the maximum and minimum temperature of a year, respectively.



a) Temperatures in Beijing from 1995 to 2005 b) Modeled yearly temperature variation

Fig. 2. Yearly temperature variation in pavement structure

Daily temperature variation is very complicated due to the difference in the daytime and nighttime as well as sunny or cloudy weather. Without considering the cloudy days, daily temperature variation also can be described by a sine function. Based upon a large amount of measurement data, it can be found that the temperature on the pavement surface at 8 am is roughly equal to that at 6 pm, and the highest (maximum) temperature occurs at 2 pm and lowest (minimum) occurs at 2 am in most cities in the Central China. Therefore, the time for the highest temperature and time for the lowest temperature are determined based upon these data. The daily temperature variation can be formularized as follows:

$$T_a(t,z) = [T_y + \widetilde{T}_y \sin(\omega(t - 365 \times 6))]\alpha_y \sin^2(\omega_o(t-8))e^{-\alpha_1 z} \tag{4}$$

where, α_y is the daily maximum/minimum temperature effect coefficient, which can be defined as

$$\alpha_y = \frac{1}{2}\left(\frac{T_d^{\max}}{T_y^{\max}} + \frac{T_d^{\min}}{T_y^{\min}}\right) \tag{5}$$

and, $T_d^{\max}$ and $T_d^{\min}$ are the maximum and minimum temperature of a year, respectively.

3.2 Solar Radiation

Solar radiation is another source of heat on pavement structures. The quantity of heat varies periodically with variation of day and night as well as the season. Similar to the method for ambient temperature discussed in the previous subsection, the quantity of solar radiation can be expressed by a double-sine function as follows:

$$Q_a(t,z) = [Q_y + \widetilde{Q}_y \sin(\omega(t - 365 \times 6))\alpha \sin^2(\omega_0(t-6))e^{-s_2 z}] \tag{6}$$

where,

$$\left.\begin{aligned} Q_y &= \frac{1}{2}(Q_y^{\max} + Q_y^{\min}), \widetilde{Q}_y = \frac{1}{2}(Q_y^{\max} - Q_y^{\min}) \\ \alpha_Q &= \frac{1}{2}\left(\frac{Q_d^{\max}}{Q_y^{\max}} + \frac{Q_d^{\min}}{Q_y^{\min}}\right) \end{aligned}\right\} \tag{7}$$

$Q_y^{\max}$, $Q_y^{\min}$ are the maximum and minimum average annual solar radiation intensity, respectively. $Q_d^{\max}$, $Q_d^{\min}$ are the maximum and minimum average daily solar radiation intensity, respectively, and the unit is w/m^2, and S_2 is the ambient variation coefficient departing from the Earth's surface along vertical coordinate system, which is obtained by measurement.

Since the minimum average annual solar radiation intensity is zero, then α_Q in Equation (7) can be transformed to Equation (8).

$$\alpha_Q = \frac{1}{2}\frac{Q_d^{\max}}{Q_y^{\max}} \tag{8}$$

4. Temperature Field and Temperature Gradient for the Layered System

4.1 Restrictive or Boundary Conditions

To solve the temperature field from the Equation (1), the following restrictive or boundary conditions were employed in this paper namely pavement surface as boundary conditions, continuum between layers as restrictive conditions, finite value conditions and initial conditions. The details were listed in this section.

(1) Pavement Surface as Boundary Condition

In that pavement- environment system, heat transfers into pavements by three modes, i.e., thermo-conductivity, convection and radiation. According to the Fourier thermo-conductivity law, the quantity which the Earth's transfers into pavement is defined as the following Equation,

$$P = -\lambda_1 \frac{\partial}{\partial z} T_1(t,z) \tag{9}$$

Where P is the heat quantity transferring into pavements on a unit area measured with w/m^2, λ_1 is the thermo-conductivity coefficient of pavement material, with units w/(m ˚C) and $T_1(t,z)$ is the temperature field function of pavement layer measured in ˚C.

The minus sign in Equation (9) shows heat loss. When the ambient temperature and pavement surface temperature are different, convection Equation is given as according to Newton's cooling law,

$$q = a[T_a(t,z) - T_1(t,z)] \tag{10}$$

where, q is heat flow density when convection occurs on the interface between pavement and air, w/(m^2 ˚C). Then while $T_a(t,z) > T_1(t,z)$, pavement obtains heat from environment, and when $T_a(t,z) < T_1(t,z)$, it gives off heat into environment.

Radiation between pavement and environment is reciprocal. According to Stefan-Boletzman radiation law, the radiation quantity on unit area between pavement and environment can be determined using Equation (11),

$$R = \varepsilon\ C_0[T_a^4(t,z) - T_1^4(t,z)] \tag{11}$$

where, R is the heat flow density when convection occurs on the interface between pavement and air measured in w/m^2, ε is blackness degree on pavement; C_0 is radiation constant, $C_0 = 5.67 \times 10^{-8} w/(m^2 k^4)$,

In addition, while $T_a(t,z) > T_1(t,z)$ environment emits heat on the pavement, and vice versa.

The concurrence phenomenon of convection and radiation is called composite heat exchange in conduct-calorifics. The total density of composite heat exchange is determined with Equation (12),

$$\overline{R} = R + q = \varepsilon C_0[T_a^4(t,z) - T_1^4(t,z)] + a[T_a(t,z) - T_1(t,z)] \qquad (12)$$

Radiation heat-exchange coefficient is introduced as Equation (13),

$$a_R = \frac{\varepsilon C_0[T_a^4(t,z) - T_1^4(t,z)]}{T_a(t,z) - T_1(t,z)} \qquad (13)$$

Then Equation (11) can be rewritten as Equation (14),

$$R = a_R[T_a(t,z) - T_1(t,z)] \qquad (14)$$

When replacing the R in Equation 12, and introducing the coefficient a_b, then the composite heat-exchange density can be written as Equation 15,

$$\overline{R} = a_b[T_a(t,z) - T_1(t,z)] \qquad (15)$$

where, a_b is the composite heat-exchange coefficient in w/(m²•°C), and

$$a_b = a_R + a \qquad (16)$$

Solar radiation is the main source of heat on the pavement. Taking pavement reflection into account the heat density in pavement obtained from solar radiation can be formularized as Equation (17),

$$q_s = a_s Q_a(t,z) \qquad (17)$$

where, a_s is solar radiation absorptivity of the pavement material.

Summarizing the discussions above, thermo-Equation condition on the surface of pavement can be defined as Equation (18).

$$-\lambda_1 \frac{\partial}{\partial z} T_1(t,z) + a_b[T_a(t,z) - T_1(t,z)] + a_s Q_a(t,z)\Big|_{z=0} = 0 \qquad (18)$$

(2) Continuum Conditions between Layers

Based on the assumption that layers were bonded tightly and therefore could be considered as continuum, the continuum conditions could be described as Equation. (19) and (20),

$$T_j(t,z)\Big|_{z=h_j} = T_{j+1}(t,z)\Big|_{z=h_j} \qquad (19)$$

$$\lambda_j \frac{\partial T_j(t,z)}{\partial z}\Big|_{z=h_j} = \lambda_{j+1} \frac{\partial T_{j+1}(t,z)}{\partial z}\Big|_{z=h_z} \qquad (20)$$

(3) Finite Value Condition

When only the temperatures of the pavement surface were considered as the finite value condition, it could be easily expressed, as shown in Equation (21),

$$T_3(t,z)\Big|_{z\to\infty} \neq \infty \qquad (21)$$

(4) Initial Condition

In the study on non-stable constant temperature field, the initial condition should usually be presented. However, for research work on temperature field for composite pavement under environmental effects, the initial condition is insignificant. The initial state has no effect on the present-day's Earth's surface temperature. For pavement structures, from construction to traffic operation, it would go through a relatively long period during which environment and periodic variation on the Earth's surface (yearly/daily variation) also make the initial condition insignificant.

4.2 Temperature Field within RCC-AC Pavement

4.2.1 Equations to Determine the Temperature Field

With the restrictive or boundary conditions, the temperature fields could be obtained with the Equation. (1). and all the Equations for the solution are listed from (22) to (25),

$$\frac{\partial T_j(t,z)}{\partial t} - \theta_j \frac{\partial^2 T_j(t,z)}{\partial z^2} = 0 \qquad (j=1,2,3) \tag{22}$$

$$\lambda_1 \frac{\partial}{\partial z} T_1(t,z)\Big|_{z=0} = a_b[T_a(t,z) - T_1(t,z)] + a_s Q_a(t,z)\Big|_{z=0} \tag{23}$$

$$\left.\begin{aligned} & T_j(t,z) - T_{j+1}(t,z)\Big|_{z=h_j} = 0 \\ & \lambda_j \frac{\partial T_j(t,z)}{\partial z} - \lambda_{j+1}\frac{\partial T_{j+1}(t,z)}{\partial z}\Big|_{Z=h_j} = 0 \qquad (j=1.2) \end{aligned}\right\} \tag{24}$$

$$T_3(t,z)\Big|_{z\to\infty} = \infty \tag{25}$$

4.2.2 General Solution for Equations of the Temperature

Then with the Equations from (22) to (25), the general solution for the RCC-AC pavement was discussed as follows.

Due to the effect of solar radiation and ambient temperature, the pavement surface, even for the whole composite pavement structure, takes on periodic variations which are similar to the relationship between environment and time. In the expression for simulating ambient temperature, the yearly and daily temperature variation can be expressed as $\sin(\omega(t-365\times 6))$ and $\sin^2(\omega(t-8))$. Therefore these two factors are considered in the composite pavement: $T_j(t,z) = Z_j(z)\sin(\omega(t-365\times 6))\sin^2(\omega_0(t-8))$

For easier derivation, complex number is introduced in Equation (26),

$$e^{i\varphi} = \cos\varphi + i\sin\varphi \tag{26}$$

Then Equation (15) is turned into (27).

$$T_j = (t\cdot z) = Z_j(z)e^{i[(\omega+2\omega_0)t-11\pi/6]} \tag{27}$$

Assuming only the imaginary number part is adopted, that is

$$T_j(t\cdot z) = Z_j(z) I_m e^{i[(\omega+2\omega_0)t-\frac{11\pi}{6}]} \tag{28}$$

Then

$$Z_j(z) = A_j e^{\frac{\sqrt{(\omega+2\omega_0)i}}{\theta_j}} z + B_j e^{-\frac{\sqrt{i(\omega+2\omega_0)}}{\theta_j}z} \tag{29}$$

When assuming

$$\mu_j = \sqrt{\frac{\omega+2\omega_o}{\theta_j}} \qquad (j=1,2,3) \tag{30}$$

and note that $\sqrt{i} = \frac{1}{\sqrt{2}} + i\frac{1}{\sqrt{2}}$, then Equation (29) can be turned to

$$Z_j(z) = A_j e^{\mu_j z} e^{i\mu_j z} + B_j e^{-\mu_j z} e^{-i\mu_j z} \tag{31}$$

When substituting Equation (31) with Equation (25), the general solution for the layer system can be obtained.

$$T_j(t \cdot z) = \frac{1}{2}(A_j e^{\mu_j z} - B_j e^{-\mu_j z}) \sin(wt - \frac{\pi}{2}) \Big\{ \sin \mu_{jz} - \frac{1}{2}[\sin(\mu_{jz} + 2\omega_0 t - 4\pi/3) + \sin(\mu_{jz} - 2\omega_0 t + 4\pi/3)] \Big\} \tag{32}$$

Equation (32) is the expression for the temperature field for the layered system. It was shown in Equation (32) that that the phase of the pavement temperature lagged with the depth, and the pavement temperature is a function of ω and ω_0. It also shows that the annual maximum temperature appears from the end of June to the early of July. For daily variation in pavement structure, according to the last factor in Equation (25), it indicates that the daily maximum temperature and minimum temperature occur at 14 pm and 2 am, respectively.

4.2.3 Determine Required Constants with MWR

To determine the required constants A_j and β_j (j=1, 2, and 3) in Equation (32), substitute Equation (32) into solution condition (22)~(24), and then utilize the moment method of method of weighted residue (MWR) to eliminate variable t, in the process weight function take:

$$\varphi = t$$

On the condition of weight average, all the solution conditions are met; therefore Equation (22) to (24) can be rewritten as follows,

$$\frac{1}{24}\int_0^{24} f_i(t)dt = 0 \tag{33}$$

Where, $f_i(t)(i = 1,2,3,4,5)$, utilizing Equation (33) the coefficient A_j and $\beta_j\,(j = 1,2,3)$ can be determined.

4.3 Temperature Gradient

After receiving the temperature field, the temperature gradation could be expressed easily according the definition of gradients, and shown as Equation (34),

$$gradT_j(t,z) = \frac{1}{2}\mu_j \sin(\omega t - \frac{\pi}{2}) \Big\{ A_j e^{\mu_{jz}} \{ \sin \mu_{jz}[1 - \cos(2\omega_0 t - 4\pi/3)] + \cos \mu_{jz}[1 - \cos(2\omega_0 t - 4\pi/3)] \} + B_j e^{-\mu_{jz}} \{ \sin \mu_{jz}[1 - \cos(2\omega_0 t - 4\pi/3)] - \cos \mu_{jz}[1 - \cos(2\omega_0 t - 4\pi/3)] \} \Big\} \tag{34}$$

5. Calibration with RCC Slab

In practices of composite pavements, RCC slab were given the most attention, therefore, the temperature gradients of the RCC slabs were discussed as the calibration for this research. The details are listed as follows:

If the real measurement in Central China is used as an example, thermo-coefficient λ_1=0.37w/(m ˚C), λ_2=1.08w/(m ˚C), λ_3=1.16w/(m ˚C), Q_1=0.4624m^2/h, Q_2=2.1384m^2/h, Q_3=2.7108m^2/h, a_b=8.9452×10^4 w/(m^2 ˚C), and also a_s as 0.80, and 0.93 for the RCC slab and asphalt pavement, respectively.

When the pavement structure dimensions are, 0, 2, 4, 6, 8, 10, and 12 cm for asphalt pavement layers, respectively, for cement concrete slabs as 22 cm. According to the five- year data from the weather stations, the average temperature gradients in RCC slab are calculated. Fig. 3 shows the average temperature gradient in RCC layer. As expected, the average temperature gradient in RCC layer decreases linearly with the increase of the asphalt pavement overlay thickness. Fig. 4 shows the temperature gradient in the RCC with the slab thickness variation for different thickness of the asphalt concrete (AC) pavement overlay. Further experimental data are in observation. The current study is comparing the numerical analysis and the experimental data as well as the predictions from other models.

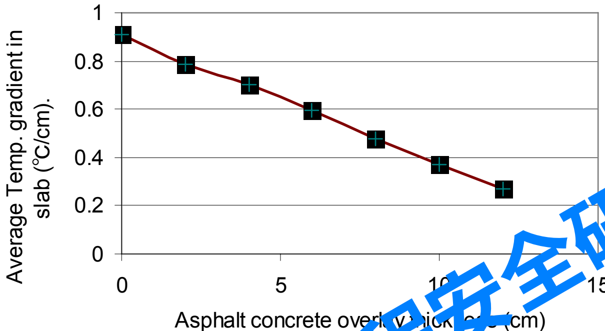


Fig. 3. The average temperature gradient of in the RCC slab vs. the asphalt overlay thickness

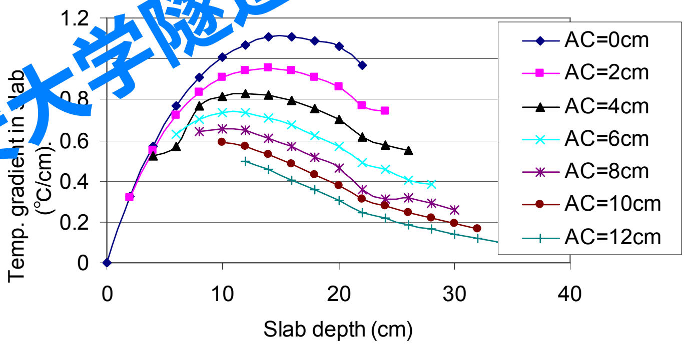


Fig. 4. The temperature gradient in the RCC slab across a range of slab depth (from the top of the overlay surface to the RCC slab) for different asphalt overlay thickness

6. Summary and conclusion

In this paper, based upon the thermo-conductivity theory, the temperature field for composite pavements was analyzed and the Equations for the temperature field and the temperature gradient were derived by considering the yearly temperature variation. Moreover, the temperature gradient in RCC slab was computed. Through the computation, it was found that the temperature gradient shows non-linear distribution in RCC with the slab depth variation and non-linearity weakens with slab thickness increasing, during which maximum gradient value approaches the temperature of the RCC surface.

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