Predicting Maximum Pavement Surface Temperature Using Maximum Air Temperature and Hourly Solar Radiation

MANSOUR SOLAIMANIAN AND THOMAS W. KENNEDY

A simple method is proposed to calculate the maximum pavement temperature profile on the basis of maximum air temperature and hourly solar radiation. The method was developed to be used mainly for Strategic Highway Research Program binder and mixture specifications and as a quick method of determining maximum pavement temperature for various regions in the United States and Canada. The method is based on the energy balance at the pavement surface and the resulting temperature equilibrium. Reasonable assumptions are made regarding thermal properties of the asphalt concrete. The accuracy of the method was tested by applying it to some field cases for which measured pavement temperatures were available. In 83 percent of the cases, the proposed equation predicted the pavement temperature within 3°C, which is well within reasonable limits, considering the numerous uncertainties that exist in material properties, accuracy of measurements, variability of environmental factors (wind, sunshine, etc.), and inclination of the pavement surface in receiving radiation.

The binder and mixture specifications that are in development under the Strategic Highway Research Program (SHRP) Asphalt Research Program are tied to maximum and minimum pavement temperatures for various locations in the United States and Canada. Therefore, it became necessary to seek a quick and efficient way to determine the maximum pavement temperature profile with sufficient accuracy for various regions. Barber (*1*) was among the first researchers to propose a method of calculating maximum pavement temperature from weather reports. He applied a thermal diffusion theory to a semi-infinite mass (pavement) in contact with air. In his theory, solar radiation was considered on the basis of its effect on the mean effective air temperature. The resulting equation is simple. However, because the method uses total daily radiation rather than hourly radiation, the calculated maximum pavement temperature with this model is the same for different latitudes having the same air temperature conditions and the same total daily solar radiation.

Another procedure was suggested by Rumney and Jimenez (*2*). They developed some empirical nomographs to predict pavement temperature at the surface and at a 2-in. depth as a function of air temperature and hourly solar radiation. These graphs were developed on the basis of data collected on pavement temperature in Tucson, Arizona, in June and July along with data collected on measured hourly solar radiation. Dempsey (*3*) developed an analysis program, named climatic-materials-structural (CMS) model, that is based on heat transfer theory and energy balance at the surface. A finite difference approach is used to deal with the resulting differential equation. The CMS model uses a regression equation to calculate the incident solar radiation from the extraterrestrial radiation. The program is useful for providing detailed information about pavement temperature variations during the day for a sequence of days. However, the program requires a considerable amount of input. The method proposed here can be used when one is interested in determining just the maximum pavement temperature with a minimum amount of input. One can also directly use the charts that are developed for this purpose. The method is very simple and quick: a user who knows the latitude of the location and the air temperature can use the charts to find a reasonable estimate of the maximum pavement temperature. The method is developed on the basis of the theory of heat transfer and takes into account the effect of latitude on solar radiation.

The University of Texas at Austin, Austin, Tex. 78701.

THEORY

The net rate of heat flow to and from a body, q_{net}, can be calculated from the equation

$$q_{net} = q_s + q_a + q_t \pm q_c \pm q_k - q_r$$

where

- q_s = energy absorbed from direct solar radiation,
- q_a = energy absorbed from diffuse radiation (scattered from the atmosphere),
- q_t = energy absorbed from terrestrial radiation,
- q_c = energy transferred to or from the body as a result of convection,
- q_k = energy transferred to or from the body as a result of conduction, and
- q_r = energy emitted from the body through outgoing radiation.

q_s and q_a are always positive for the surface of a body such as pavement exposed to radiation. The terrestrial radiation, q_t, is positive for a body that is above the surface of the earth or is tilted so that it can "see" the earth surface. For the pavement surface, q_t can be considered to be 0. The convection energy is transferred from the pavement to the surrounding air if the former has a higher temperature than the latter. In this case, q_c appears with a negative sign in the above formula for a pavement. The conduction energy appears with a positive sign if the surface temperature is lower than the temperature at a depth below the surface (as might be the case during cold winter days). Conduction energy will have a negative sign when the surface temperature is higher than the pavement temperature at other depths. This is especially true during the hot days of summer. Finally, the energy emitted from the pavement surface, q_r, is always negative. Therefore, during summer, when the greatest interest in predicting the maximum pavement temperature exists, the net rate of heat flow to the surface of the pavement can be written as

$$q_{\text{net}} = q_s + q_a - q_c - q_k - q_r \tag{1}$$

Each of the quantities in this heat flow equation is discussed later.

Direct Solar Radiation

The energy absorbed from direct solar radiation, q_s, can be calculated as

$$q_s = \alpha \cdot R_i \tag{2}$$

where α is the surface absorptivity to the solar radiation and R_i is the incident solar radiation.

The part of the incident solar radiation that is not absorbed by the surface $[(1 - \alpha_{\text{solar}}) \cdot R_i]$ will be reflected back to the atmosphere.

The surface absorptivity α depends on the wavelength of the incoming radiation. For some materials α varies within a very wide range depending on the wavelength. For example, polished brass has an absorptivity of about 0.08 for long-wave radiation (9.3 μm) at 100°F and 0.49 for solar radiation that is considered shortwave radiation (less than 2 μm). White paper has an absorptivity of about 0.95 to long-wave radiation and 0.28 to shortwave radiation. For asphaltic materials it seems that α_{solar} does not vary substantially over a wide range. Typically α_{solar} for asphalt mixtures varies from 0.85 to 0.93.

The incident solar radiation R_i depends on the angle between the direction of the normal to the surface receiving radiation and the direction of the solar radiation and can be calculated as

$$R_i = R_n \cdot \cos i \tag{3}$$

where

R_n = the radiant energy incident on a surface placed normal to the direction of the rays of the sun and
i = the angle between the normal to the surface and the direction of radiation.

R_n can be calculated from the solar constant R_0, which is the impinging rate of the solar energy on a surface of unit area placed normal to the direction of the sun rays at the outer fringes of the earth's atmosphere. The solar constant is about 1394 W/m² (442 Btu/hr ft²). The rate of solar energy received at the surface is substantially less than the solar constant because a large portion of the radiation is absorbed by the atmosphere and its contents before reaching the earth. Gases, clouds, and suspended particles in the atmosphere scatter and reflect about 26 percent of insolation (incoming solar radiation) into space. The atmosphere and the earth's surface together absorb about 70 percent of insolation. The solar energy received at the surface depends on the location, time of the day, and time of the year. The value of R_n can be calculated as

$$R_n = R_0 \tau_a^m \tag{4}$$

where

R_0 = solar constant;
m = relative air mass, defined as the ratio of the actual path length to the shortest possible path; and
τ_a = transmission coefficient for unit air mass.

The value of τ_a is less in the summer than in the winter because the atmosphere contains more water vapor during the summer. The value also varies with the condition of the sky, ranging from 0.81 on a clear day to 0.62 on a cloudy one.

The relative air mass m is approximately equal to $1/(\cos z)$, where z is the zenith angle (the angle between the zenith and direction of the sun's rays).

The zenith angle depends on the latitude ϕ, the time of day, and the solar declination. The time is expressed in terms of the hour angle h (the angle through which the earth must turn to bring the meridian of a particular location directly under the sun). At local noon h is 0, but in general it depends on the latitude and the solar declination, δ. The zenith angle can be found from

$$\cos z = \sin \phi \sin \delta_s + \cos \delta_s \cos h \cos \phi \tag{5}$$

For horizontal surfaces $\cos i = \cos z$, but for a surface that is tilted at an angle ψ degrees to the horizontal, i can be obtained from

$$\frac{R_i}{R_n} = \cos i = \cos|z - \psi| - \sin z \sin \psi + \sin z \,\psi \sin |A - \beta| \tag{6}$$

where

ψ = tilt angle,
A = the azimuth of the sun, and
β = the angle between the south meridian and the normal to the surface measured westward along the horizon.

Development of the preceding formulas was explained elsewhere (*4*).

The solar and surface angles for a tilted surface are shown in Figure 1. Brown and Marco (*5*) have developed graphic relationships from which the values of the required angles can be obtained for northern latitudes. One of these graphs giving solar angles for the period from May to August for latitudes between 25°N and 50°N is shown in Figure 2.

Atmospheric Radiation

Atmospheric radiation absorbed by the pavement surface may be calculated through the following empirical formula developed by Geiger (*6*) and reported by Dempsey (*3*):

$$q_a = \varepsilon_a \sigma T_{\text{air}}^4 \tag{7}$$

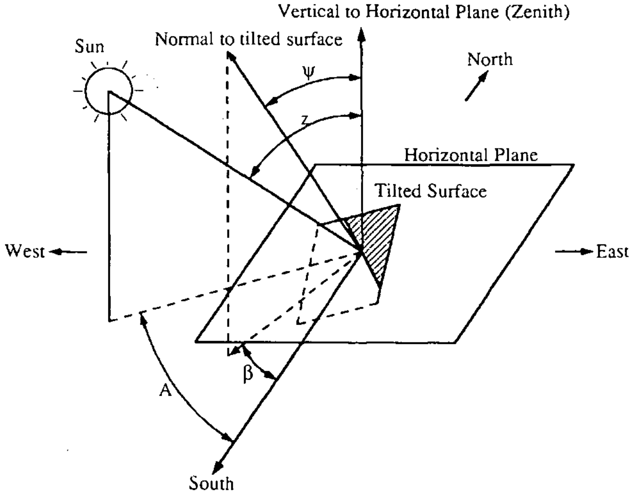

FIGURE 1 Definition of solar and surface angles for Equation 6 (*4*).

where

$\varepsilon_a = G - J\,(10^{-\rho P})$,
σ = Stefan-Boltzman constant = 5.68×10^{-8} W (m^2 °K^4),
T_{air} = the air temperature (°K), and
ρ = the vapor pressure varying between 1 and 10 mm of mercury.

G, J, and P can be represented by constant values of 0.77, 0.28, and 0.074, respectively, according to Geiger (*6*).

Conduction Energy

The conduction rate of heat flow from the pavement surface down can be approximately calculated as

$$q_k = -k\,\frac{T_d - T_s}{d} \tag{8}$$

where

k = thermal conductivity,
T_s = surface temperature,
d = depth, and
T_d = temperature at depth d.

Radiation Energy Emitted from the Surface

The rate at which the surface emits radiation is given by

$$q_r = \varepsilon\sigma T_s^4 \tag{9}$$

where ε is emissivity.

Emissivity as well as absorptivity is involved in any heat transfer by radiation. For a body at the same temperature, they have the same numerical value. However, as mentioned before, absorptivity may be significantly different from emissivity if the radiation absorptivity is not from a black body or if it is from a body at a very high temperature (such as the sun). For asphaltic materials, the emissivity and absorptivity to shortwave radiation (such as solar absorptivity) have been reported to be identical (about 0.93).

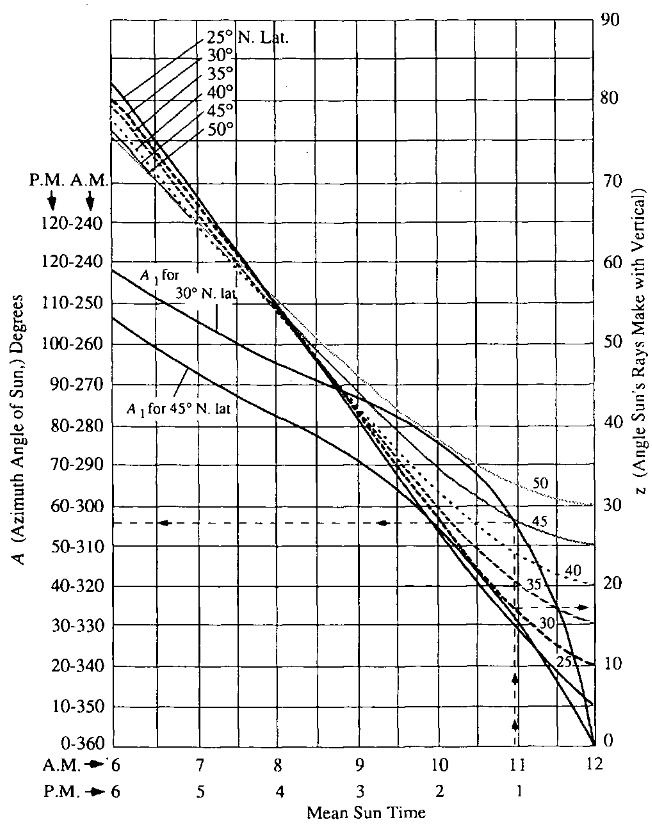

FIGURE 2 Solar angles for the period from May to August in northern latitudes (*5*).

Convection Energy

The rate of heat flow by convection to the surrounding air is given by

$$q_c = h_c(T_s - T_{air}) \tag{10}$$

where h_c is the surface coefficient of heat transfer (average convective heat transfer coefficient).

In general, h_c depends on the geometry of the surface, the wind velocity, and the physical properties of the fluid (in this case air). In many cases, it also depends on the temperature difference.

Equilibrium Temperature at the Pavement Surface

The equilibrium temperature at the pavement surface can be obtained by setting the net rate of heat flow, q_{net}, equal to 0.

$$q_s + q_a - q_c - q_k - q_r = 0 \tag{11}$$

Then, by writing each of the above flow rates in terms of temperatures, an equation involving surface temperature, air temperature, and temperature at a depth can be obtained. The air temperature should be available through measurement. Reasonable assumptions could be made about the temperature difference between the surface and a particular depth. The final equation obtained in this way will be the following fourth-degree equation, which can be solved to yield the surface temperature.

$$422\alpha\tau_\alpha^{1/\cos z} \cdot \cos z + \varepsilon_a\sigma T_a^4 - h_c(T_s - T_a) - \frac{k}{d}(T_s - T_d) - \varepsilon\sigma T_s^4 = 0 \qquad (12)$$

Maximum Pavement Temperature and Required Thermal Parameters

Maximum air temperature and maximum hourly direct solar radiation can be used to calculate the maximum pavement temperature. The maximum hourly solar radiation is obtained by using the minimum z angle from the Brown and Marco chart. This angle has the lowest value at noon sun time for different latitudes. For the months between May and August, at the noon sun time, z can be approximately calculated as

$$z = \text{latitude} - 20 \text{ degrees} \qquad (\text{for latitude} > 22 \text{ degrees})$$

The value of τ_α for calculation purposes is assumed to be 0.81, which represents a clear sunny day.

An investigation of several different sets of data concerning maximum temperature difference between the surface and a 2-in. depth during hot summer days indicates that this difference varies between 10°F and 20°F with an average value of 15°F. Calculated maximum pavement temperatures reported in this paper are based on the 15°F difference assumption.

The coefficient ε_a for atmospheric radiation, as defined in empirical Equation 7, depends on vapor pressure. A change in vapor pressure from 1 to 10 mm of mercury increases ε_a from 0.53 to 0.72. The calculated atmospheric radiation varies between 246 and 331 W/m² (78 and 105 Btu/hr/ft²) in extremes for an air temperature of 27°C (80°F). The variation is between 284 and 378 W/m² (90 and 120 Btu/hr/ft²) for an air temperature of 38°C (100°F). Therefore, the effect of vapor pressure on changing the atmospheric radiation is not significant, considering the magnitude of other forms of radiation that are involved in the surface energy balance. A value of 0.70 was adopted for ε_a, considering the above discussion and the fact that during the summertime the vapor pressure is higher than at other times of the year.

The most reasonable values for thermal parameters α (solar absorptivity), ε (emissivity), k (thermal conductivity), and h_c (surface heat transfer coefficient) need to be input to obtain the best estimate of the maximum pavement temperature.

The emissivity of a surface varies with temperature, its degree of roughness, and oxidation. Therefore, the emissivity in a single material may vary within a wide range. Absorptivity depends on the same parameters as emissivity as well as the nature of the incoming radiation and its wavelength. For asphalt materials, it seems that these two parameters vary within a narrow range (0.85–0.93).

The range of variation in the thermal conductivity of asphalt concrete appears to be significantly larger than that of absorptivity and emissivity. Highter and Wall (*7*) report that values of thermal conductivity for asphalt concrete range from 0.74 to 2.89 W/m² °C (0.43 to 1.67 Btu/hr/ft² °F/ft) after reviewing a considerable number of references regarding this property. Because aggregate is the major portion of the asphalt concrete, it seems reasonable to assume that significant variations in thermal properties of the aggregates cause large differences in the thermal conductivity of the asphalt concrete.

The surface coefficient of heat transfer seems to be more difficult to determine than the other parameters. The coefficient h_c is not really a thermal property of the material in the same sense that k is. It is not a constant and depends on a lot of variables. It is mainly used to yield a simple relationship for convection heat transfer.

The empirical formula developed by Vehrencamp (*8*) and reported by Dempsey (*3*) appears to be the most suitable for determining h_c for a pavement surface.

$$h_c = 698.24[0.00144\ T_m^{0.3}U^{0.7} + 0.00097\ (T_s - T_{\text{air}})^{0.3}] \qquad (13)$$

where

h_c = surface coefficient of heat transfer,
T_m = average of the surface and air temperature in °K,
U = average daily wind velocity in m/sec,
T_s = surface temperature, and
T_{air} = air temperature.

The expression in brackets yields the convection coefficient h_c in terms of gram calories per second square centimeter degree Celsius. The factor 698.24 is used to give the result in terms of Watts per square meter degree Celsius. For an average wind velocity of about 4.5 m/sec (10 mph) and for typical ranges of maximum air and pavement temperatures, the formula yields a value varying between 17 and 22.7 W/m² °C [3 and 4 Btu/(hr/ft² °F)].

Sensitivity Analysis

A sensitivity analysis was performed to investigate the effect of various thermal parameters on the predicted maximum pavement temperature. Some of the results of the sensitivity analysis are shown in Figures 3 and 4. Essentially a linear relationship is observed between calculated maximum pavement temperature and solar absorptivity. The relationship between thermal conductivity and maximum pavement temperature is also approximately linear. As expected, surface temperature drops as thermal conductivity or absorptivity increases.

The results reported in this paper are for the following typical thermal parameters: for asphalt concrete, $\alpha = 0.9$; $\varepsilon = 0.9$; $k = 1.38$ W/m² °C; $h_c = 3.5$ W/m² °C.

Comparison of Measured and Predicted Temperatures

Discrepancies between the measured and calculated pavement temperatures are unavoidable because of the influence

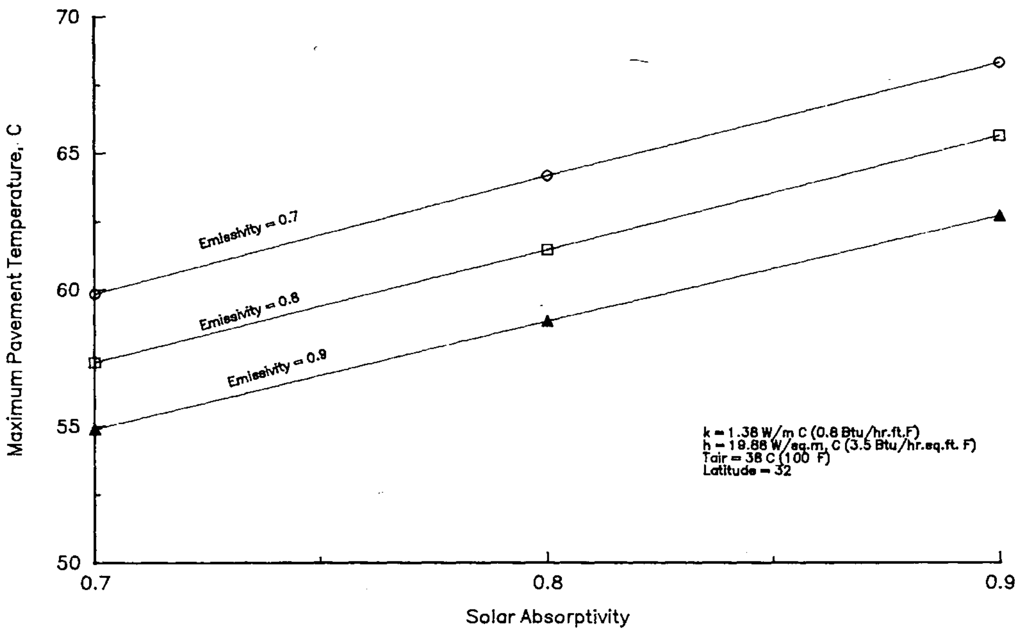

FIGURE 3 Calculated maximum pavement temperature as a function of solar absorptivity for various values of emissivity.

of a large number of factors and their corresponding variations. These discrepancies are important to consider for comparison purposes.

One question concerns the accuracy of field temperature measurements at the surface. A thermometer sitting on the pavement surface will probably yield a different reading from a thermocouple implanted into the surface. The wind velocity can influence the surface temperature through its impact on convection heat transfer. Even though it may not be significant, considering the typical range of values for this parameter, the effect of wind velocity can make some slight contribution to differences between measured and predicted values. Also a slightly cloudy day versus a perfectly sunny condition can cause small changes. In many cases, the effect of cloudiness and the percent sunshine are considered by applying a reduction factor to solar radiation. Such a reduction factor is typically obtained from a regression equation for different locations. Obviously some probability and approximation are

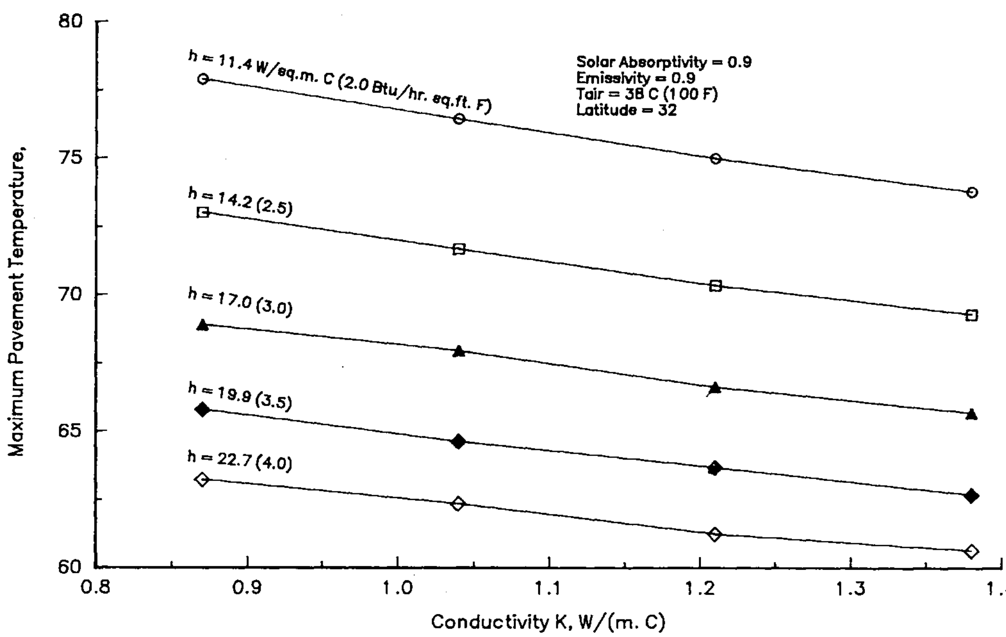

FIGURE 4 Calculated maximum pavement temperature as a function of coefficient of thermal conductivity for various values of the surface coefficient of heat transfer.

involved in obtaining such a reduction factor. It also makes a difference which part of the sky is cloudy and at what time of the day cloudiness occurs.

Another important factor is that the input parameters, especially thermal properties, are not exactly known for these field cases, and typical values reported for these parameters are used here for calculation purposes. These values are used on the basis of reasonable assumptions, previous measurements, or empirical formulas.

Another factor is the inclination of the pavement surface with respect to the direction of the sun rays. Obviously a surface inclined toward the sun rays receives more radiation than a horizontal surface, and a horizontal surface receives more radiation than a surface inclined in the opposite direction of the sun rays. In Figure 5 maximum hourly solar radiation of a horizontal surface is compared with that of a surface normal to the sun rays. Even though such inclinations may not be significant for asphalt pavements, they can create discrepancies between measured and calculated values if the effect is not considered.

Considering that there is a lot of uncertainty with respect to the factors discussed earlier and their effects, one should not expect to match the measured values very closely. The calculated values should be considered as typical pavement temperatures for a certain location. The validity of the approach presented here is investigated by comparing the predicted and measured surface temperatures, taking into consideration the preceding points.

Using the equilibrium temperature discussed above and appropriate values for variables τ, α, ε, k, and h_c, the maximum surface temperature was calculated for a number of cases for which measured pavement surface temperature was available. The cases investigated here include sites in Virginia, Arizona, Saskatchewan (Canada), Idaho, and Alabama. Information about these cases (except Alabama) can be found in previous work (*1,2,9,10*). The results are shown in Table 1 and Figure 6. This equation predicts the pavement temperature with reasonable accuracy, considering the previous discussion about the uncertainties involved. The correlation coefficient and the R^2 value are 0.91 and 0.82, respectively. Ninety-six percent of the measurements are within 4°C difference, and 83 percent are within 3°C difference.

Effect of Latitude

A useful feature of the present equation in predicting the maximum pavement temperature is that it takes advantage of the maximum hourly solar radiation rather than the total daily radiation. During the hot summer months, daily terrestrial radiation is almost the same for both northern and southern regions (Figure 7). However, the hourly radiations are different. Southern regions of the United States (lower latitudes) receive more radiation per hour than do northern regions (Figure 8). Thus, higher radiation contributes to larger differences between air and pavement temperatures, as can be seen in Figures 9 and 10. Figure 10 indicates an almost linear relationship between the maximum air temperature and the calculated maximum pavement temperature. The figure implies that for the same latitude, the difference between air and pavement temperatures is almost constant and is determined by heat transfer laws of radiation, conduction, and convection. However, a parabolic relationship is observed between the latitude and the maximum pavement temperature for various air temperatures. Figure 11 shows the difference between air and pavement temperatures as a function

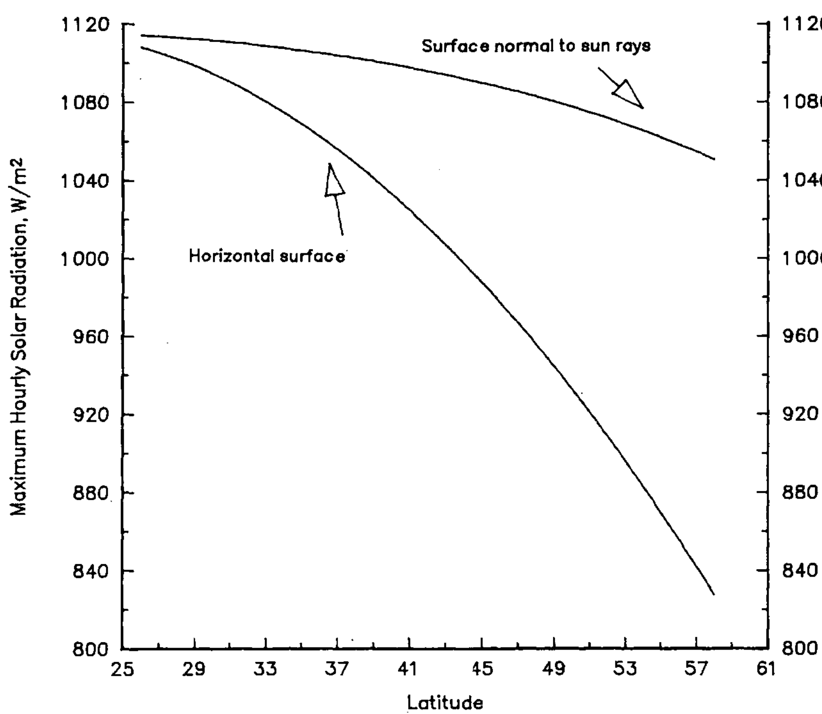

FIGURE 5 Comparison of maximum hourly solar radiation received by a horizontal surface versus a surface normal to the sun rays.

TABLE 1 Measured and Calculated Pavement Temperatures

Case	Calc. Temp., C	Measured Temp., C	Diff. Calc.-Meas.
College Park,MD	61.1	61.1	0.0
Hybla,VA	48.3	51.7	-3.3
Tucson,AZ	60.6	63.3	-2.8
Tucson,AZ	63.9	62.8	1.1
Tucson,AZ	57.8	56.7	1.1
Tucson,AZ	60.0	60.0	0.0
Saskatch,CA	41.7	41.1	0.6
Saskatch,CA	46.7	49.4	-2.8
Saskatch,CA	49.4	48.9	0.6
Saskatch,CA	51.7	46.7	5.0
Saskatch,CA	52.8	50.0	2.8
Saskatch,CA	54.4	57.2	-2.8
Saskatch,CA	54.4	51.1	3.3
Saskatch,CA	53.9	51.7	2.2
Saskatch,CA	56.1	53.3	2.8
Saskatch,CA	58.3	58.9	-0.6
Saskatch,CA	52.8	51.7	1.1
Saskatch,CA	56.1	53.9	2.2
Saskatch,CA	57.2	54.4	2.8
Saskatch,CA	57.2	56.1	1.1
Saskatch,CA	59.4	55.6	3.9
US 84, AL	59.4	56.1	3.3
Idaho	53.9	52.8	1.1
Count	23	23	23
Average	55.1	54.1	1.0
Std. Dev.	5.1	5.2	2.2
Maximum	64	63	5
Minimum	42	41	-3

of latitude. The maximum difference that occurs at lower latitudes varies between 25.5°C and 26.5°C (46°F and 48°F) when the maximum air temperature varies between 24.5°C and 42°C (76°F and 108°F). The difference at 60-degree latitude varies between 15°C and 16°C (27°F and 29°F). This figure shows that the difference between air and pavement temperatures as a function of latitude is almost independent of the air temperature (or at least the effect of air temperature can be neglected). A parabola fits the average difference data perfectly. The equation of the parabola is $\Delta T = -0.0062\ \Phi^2 + 0.2289\ \Phi + 24.38$, where Φ is the latitude and ΔT is the difference between the maximum air temperature and the maximum pavement temperature in degrees Celsius. Therefore, once latitude of a location is known, ΔT can be approximately estimated using this simple equation.

Also, in southern parts, the difference between air and calculated maximum pavement temperature is 25°C to 28°C (45°F to 50°F), whereas in northern regions it is 19.5°C to 22°C (35°C to 40°F). Moreover, the difference between air and maximum pavement temperature changes more rapidly as one moves farther north.

Temperature Variation with Depth

It is possible to approximate the temperature variation with depth once the surface temperature is known. A number of

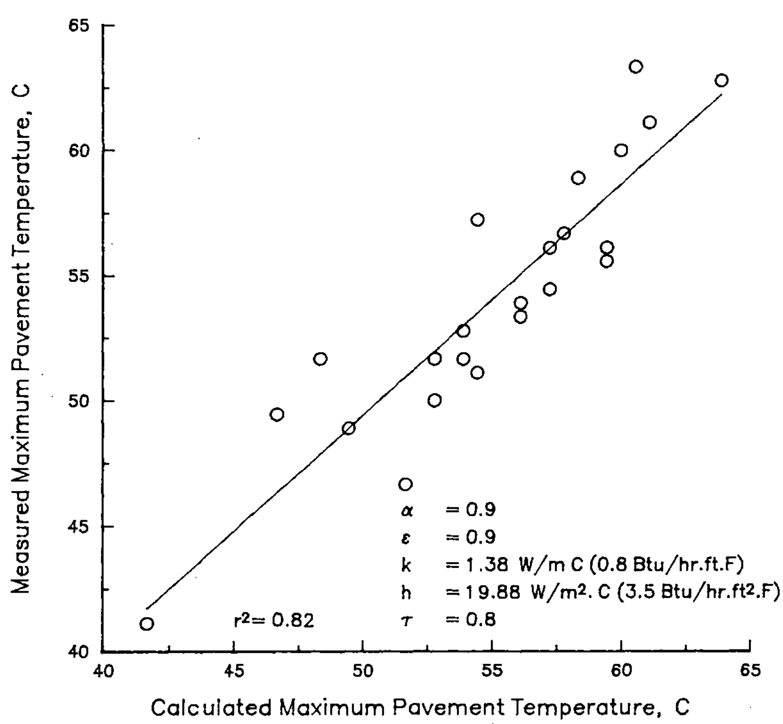

FIGURE 6 Calculated maximum pavement temperature versus measured maximum pavement temperature for various sites.

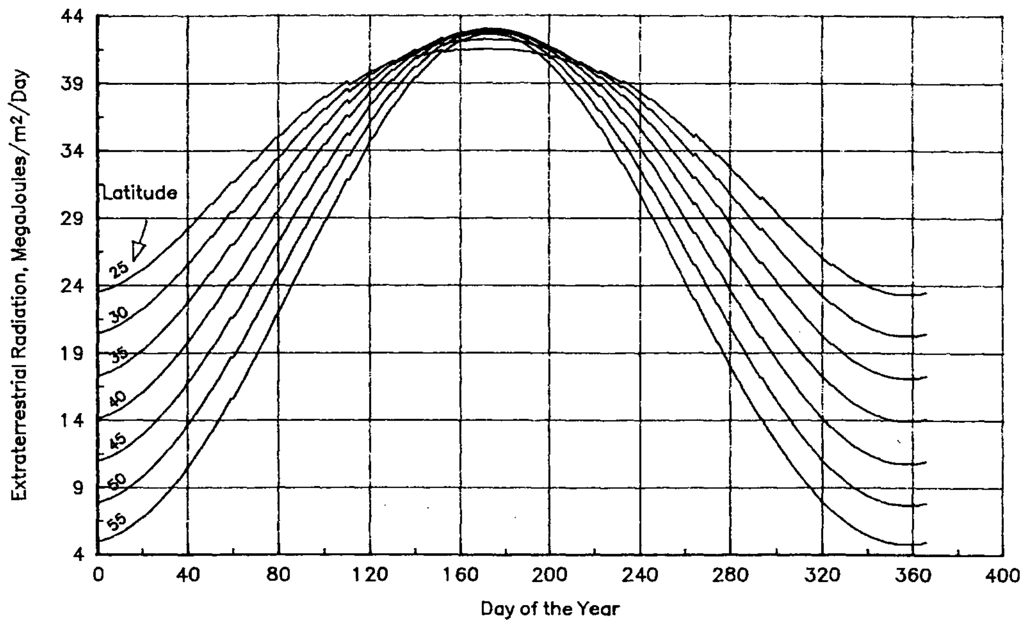

FIGURE 7 Extraterrestrial solar radiation as a function of time of year for various latitudes.

cases from Hybla, Virginia; Tucson, Arizona; and Saskatchewan, Canada, were investigated to find the best curve fitting the measured temperature profile. It was found that a cubic function of the form $T = C_0 + C_1 d + C_2 d^2 + C_3 d^3$ fits the measured data best. In this equation, coefficients C_0, C_1, C_2, and C_3 were determined for each case. These coefficients were then normalized with respect to the surface temperature, which is presented by C_0 in the preceding equation. The equation can be rewritten as

$$T = C_0\left(1 + \frac{C_1}{C_0} d + \frac{C_2}{C_0} d^2 + \frac{C_3}{C_0} d^3\right)$$

where C_1/C_0, C_2/C_0, and C_3/C_0 are normalized coefficients. Using n_1, n_2, and n_3 for these coefficients, respectively, the equation can be written in the following form:

$$T = C_0(1 + n_1 d + n_2 d^2 + n_3 d^3)$$

Once coefficients n_1, n_2, and n_3 were determined for each case, the average values were calculated. The overall cubic function was found to be in the following form:

$$T = T_s(1 - 0.063d + 0.007d^2 - 0.0004d^3)$$

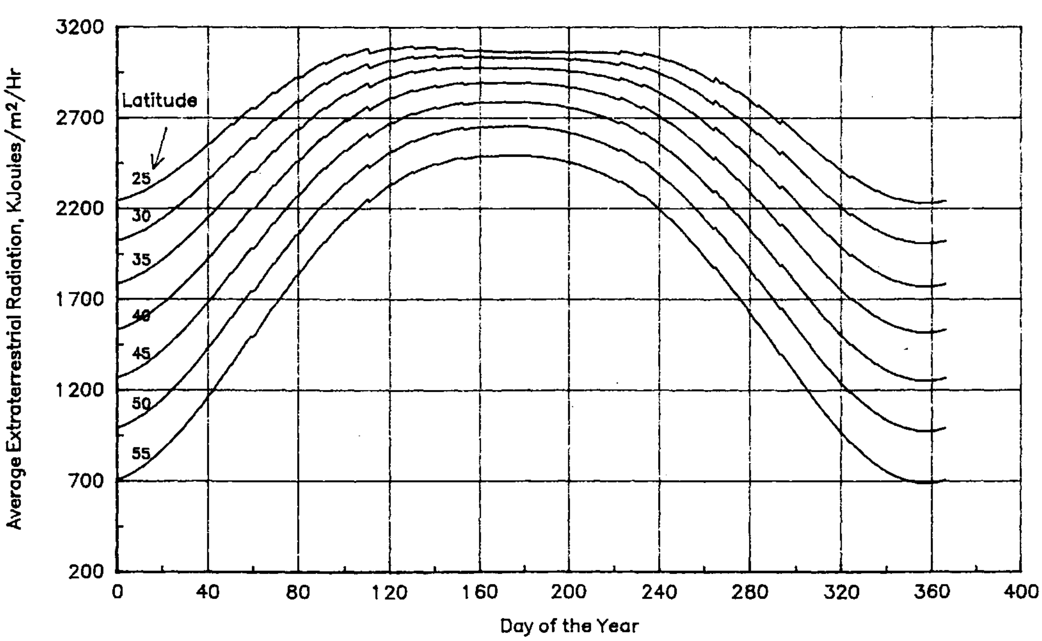

FIGURE 8 Average extraterrestrial radiation as a function of time of year for various latitudes.

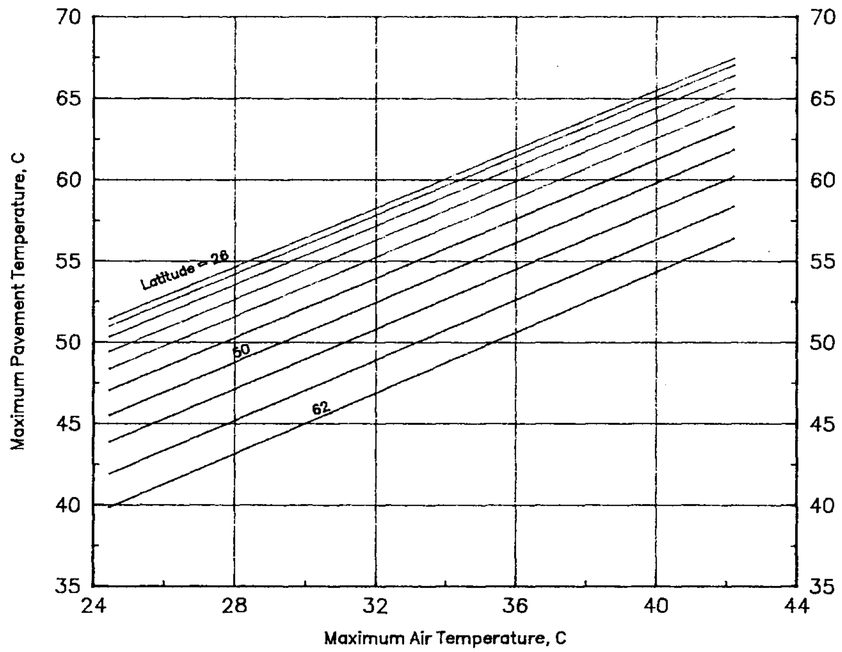

FIGURE 9 Calculated maximum pavement temperature as a function of air temperature for various latitudes.

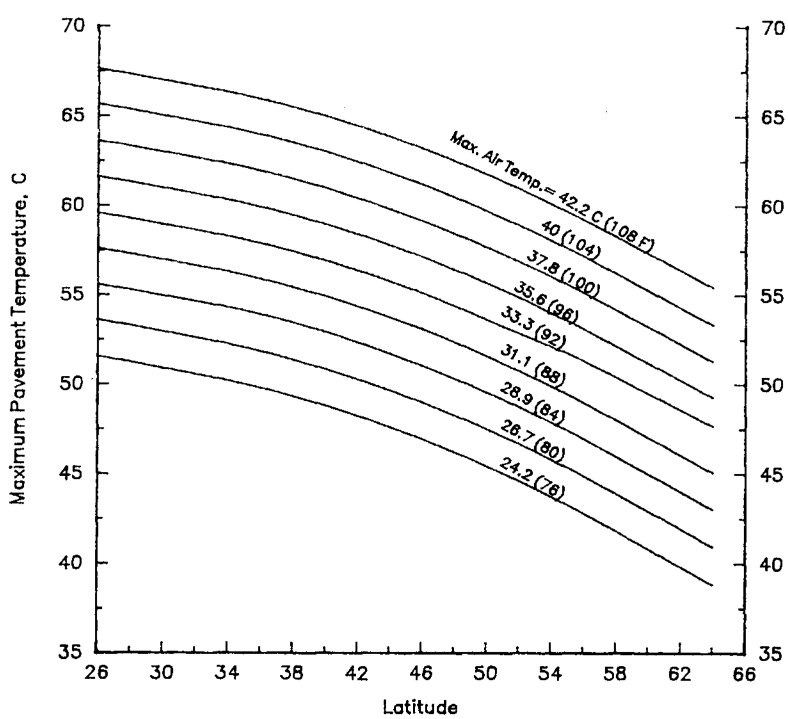

FIGURE 10 Calculated maximum pavement temperature as a function of latitude for various air temperatures.

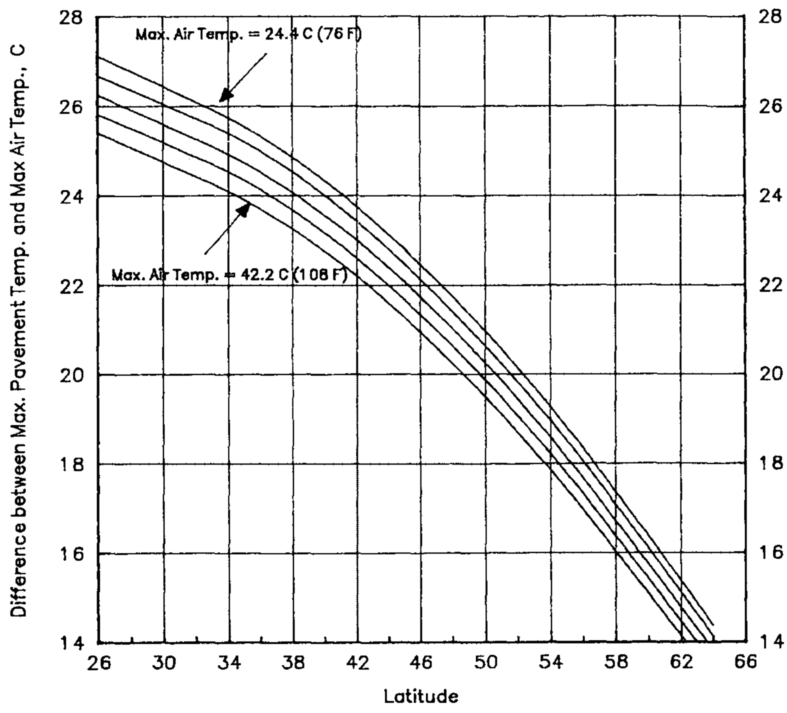

FIGURE 11 Difference between maximum pavement and maximum air temperatures as a function of latitude for various air temperatures.

where

d = depth (in.),
T_d = temperature at depth d (°F), and
T_s = the surface temperature (°F).

Note that this equation was developed for degree Fahrenheit and a conversion is needed to get the result in degrees Celsius. This equation was applied to each case. Comparison of measured and estimated temperatures at various depths indicates that within the top 20 cm (8 in.) of the pavement, the differences are 2.8°C to 3.4°C (5°F to 6°F). At higher depths, the differences are significantly larger. It may be reasonable to assume that the design temperature will be selected on the basis of the temperature distribution in the top 8 in. of the pavement, where the largest impacts on performance are observed.

Minimum Pavement Temperature

The minimum pavement temperature occurs mostly during very early morning. An analysis of a number of field cases indicates that the minimum pavement temperature during the winter is in most cases 1°C or 2°C higher than the minimum air temperature. Therefore, it seems reasonable and safe to assume that the lowest pavement temperature is the same as the lowest air temperature.

CONCLUSIONS

The following conclusions can be drawn on the basis of the results and analysis proposed in this study.

1. The proposed simple method is capable of predicting the maximum pavement surface temperature within a reasonable level of accuracy.
2. The relationship between maximum pavement temperature and maximum air temperature is essentially linear.
3. The effect of maximum hourly solar radiation in regions with the same total daily radiation is significant and cannot be ignored. This effect is considered on the basis of the latitude of the location.
4. The difference between maximum pavement temperature and maximum air temperature is expected to be lower at higher latitudes.
5. A quadratic equation perfectly fits the data representing the average difference between maximum air and maximum pavement temperatures as a function of latitude.
6. A change in absorptivity from 0.7 to 0.8 or from 0.8 to 0.9 increases the predicted maximum pavement temperature about 7°F.
7. A change in emissivity from 0.7 to 0.8 or from 0.8 to 0.9 increases the predicted maximum pavement temperature about 5°F.
8. As expected, a lower thermal conductivity results in a higher surface temperature.

REFERENCES

1. Barber, E. S. Calculation of Maximum Pavement Temperatures from Weather Reports. *Bulletin 168*, HRB, National Research Council, Washington, D.C., 1957, pp. 1–8.
2. Rumney, T. N., and R. A. Jimenez. Pavement Temperatures in the Southwest. In *Highway Research Record 361*, HRB, National Research Council, Washington, D.C., 1969, pp. 1–13.
3. Dempsey, B. J. A Heat Transfer Model for Evaluating Frost Action and Temperature Related Effects in Multilayered Pave-

ment Systems. In *Highway Research Record 342*, HRB, National Research Council, Washington, D.C., 1970, pp. 39–56.
4. Kreith, F. *Principles of Heat Transfer*, 3rd ed. Harper and Row Publishers, New York, 1973.
5. Brown, A. I., and S. M. Marco. *Introduction to Heat Transfer*, 2nd ed. McGraw Hill Book Company, Inc., New York, 1951.
6. Geiger, R. *The Climate Near the Ground*. Harvard University Press, Cambridge, Mass., 1959.
7. Highter, W. H., and D. J. Wall. Thermal Properties of Some Asphaltic Concrete Mixes. In *Transportation Research Record 968*, TRB, National Research Council, Washington, D.C., 1984.
8. Vehrencamp, J. E. Experimental Investigation of Heat Transfer at an Air-Earth Interface. *Transactions, American Geophysical Union*, Vol. 34, No. 1, 1953, pp. 22–29.
9. Kallas, B. F. Asphalt Pavement Temperatures. In *Highway Research Record 150*, HRB, National Research Council, Washington, D.C., 1966, pp. 1–11.
10. Huber, G. A., G. H. Heiman, and R. W. Chursinoff. *Prediction of Pavement Layer Temperature during Winter Months Using a Computer Model*. Canadian Technical Asphalt Association, Nov. 1989.

Publication of this paper sponsored by Committee on Characteristics of Bituminous Materials.