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Pavement surface maximum temperature increases linearly with solar absorption and reciprocal thermal inertial

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ABSTRACT

Pavement surface temperature is critical to the pavement performance and the development of cool pavements. The variations of the pavement surface temperature have been documented in numerous empirical models. These models, however, exclude critical parameters like albedo and thermal inertia but include many empirical parameters that have no thermo-physical meanings. This study presents a theoretical model to predict the surface temperature of pavements and validates it against field data and numerical results from the existing studies. It is found that the amplitude, maximum, and minimum of the pavement surface temperature increase linearly with the pavement surface absorptivity, the daily-zenith incident solar irradiation, and the reciprocal thermal inertia. Among these, raising the pavement albedo is more effective to reduce the pavement surface temperature than increasing the pavement thermal inertia. The model has practical meanings to predicting the maximum, minimum, and amplitude of the pavement surface temperature and to developing cool pavements.

1. Introduction

The pavement temperature is critical to the distresses of the pavement [1,2] and to the formation of the urban heat island [3,4]. A high daily temperature amplitude developed in a rigid pavement causes structural defects such as warping and curing [2,5–7]. A high-level surface temperature in an asphalt pavement, for instance, increases the risk of rutting [8,9]. In an urban area, a hot pavement releases a great amount of sensible heat to the ambient air and thus aggravates the urban heat island effect [10–12]. Predicting the variation of the surface temperature of a pavement is thus important for estimating the pavement performance and the urban thermal environment.

The amplitude and maximum of the surface temperature of pavements have gained numerous studies. Numerical and empirical models have been contributed to predict the pavement temperature development and to estimate the variation of the pavement surface temperature [13–24]. These models include the enhanced integrated climatic model [24], the long-term pavement performance model [23], as well as other empirical models [19–22]. In these models, the variations of the pavement surface temperature are deemed as a function of the local air temperature, the pavement depth, the latitude, and other regressed empirical coefficients. Arguments adopted in these models include the air temperature and the latitude but exclude solar irradiation. Excluding the solar irradiation in these models is unreasonable because solar radiation is the driving force for the variation of the subsurface temperature. In addition, these models fail to include the pavement thermal properties, e.g., thermal conductivity and volumetric heat capacity, resulting in inaccurate predictions to a real pavement using these models.

This study presents a theoretical model to predict the maximum, minimum, and amplitude of the pavement surface temperature. The model incorporates the pavement thermal properties, the surface albedo, and the daily-zenith incident solar irradiation. The model is validated against field data and against an extensive numerical model that is verified by observation data. The discussion is made with a focus on the use of the proposed model to predict the annual maximum surface temperature of a pavement and on the implications on the development of reflective cool pavements.

2. Methods

2.1. Heat balance at the pavement surface

The temperature variation of the earth's subsurface is driven by the solar radiation. A portion of the solar radiation is reflected back

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into the sky, which is proportional to the surface albedo, R. The remaining is absorbed and partitioned into conduction G (W/m^2), convection H (W/m^2), long-wave emission L (W/m^2), and evaporation E (W/m^2). On a dry pavement surface, the heat balance obeys Eq. (1):

$$(1-R)I = G + H + L \tag{1}$$

where I (W/m^2) is the incident solar irradiation. These factors can be further refined to:

$$(1-R)I = -k\frac{\partial T}{\partial z}\bigg|_{z=0} + h_c(T_s - T_a) + \varepsilon\sigma(T_s^4 - T_{sky}^4) \tag{2}$$

where T, T_s, T_a, and T_{sky} (K) are the temperatures of the ground, the surface, the air, and the sky, respectively; and k (W/(m K)) is the thermal conductivity of the pavement layers; z (m) is the vertical coordinate that starts from the pavement surface with positive being downward; h_c (W/(m^2 K)) is heat convection coefficient; ε is the surface emissivity and σ is the Stefan-Boltzmann constant, 5.67×10^{-8} W m^{-2} K^{-4}.

The heat transfer between a pavement and its underlying layers can be treated as a one-dimensional transient heat transfer in a semi-infinite body obeying Eq. (3):

$$c\rho\frac{\partial T}{\partial t} = k\frac{\partial^2 T}{\partial z^2} \tag{3}$$

where c (J/K) and ρ (kg/m^3) are the specific capacity and density of the ground, respectively;

Solving Eq. (3) thus needs the heat flux at the pavement surface, which can be estimated from the residual of the solar absorption, the long-wave emission, and the heat convection. The incident solar radiation I follows approximately a sinusoidal wave, with a peak at solar noon and zero at nighttime.

$$I = \begin{cases} I_0\cos(\omega t - \varphi_s), & t_{sr} < t < t_{ss} \\ 0 & t \leqslant t_{sr} \quad \text{or} \quad t \geqslant t_{ss} \end{cases} \tag{4}$$

where t_{sr} (hr) and t_{ss} (hr) are the sunrise and sunset time; φ_s (rad) is the phase of the incident solar irradiation and it is π for the local solar time.

The heat convection, h_c (T_s–T_a), is proportional to the difference between the air temperature and the pavement surface temperature. The pavement surface temperature, T_s, is inquired by numerical iterations. The air temperature, T_a, can be found from the local weather data. The following empirical formula can provide a reasonable accuracy for h_c [15,25]

$$h_c = \begin{cases} 5.6 + 4.0v & v < 5 \\ 7.2 + v^{0.78} & v \geqslant 5 \end{cases} \tag{5}$$

where v (m/s) is the wind speed measured at height of 9.0 m.

The net long-wave emission, L, is the third term at the right-hard side of Eq. (2), where the sky temperature can be estimated:

$$T_{sky} = \varepsilon_{sky}^{0.25} T_a \tag{6}$$

where the sky emissivity ε_{sky}:

$$\varepsilon_{sky} = 0.754 + 0.0044T_d \tag{7}$$

where T_d (°C) is the dew point:

$$T_d = b\gamma/(a-\gamma)$$

where a = 17.3, b = 237.7, and $\gamma = aT_a/(b+T_a) + \ln(RH/100)$ (here T_a in °C) [26].

2.2. Analytic solution to the pavement temperature

Although the daily surface temperature of a pavement varies over time, the variation approximately follows sinusoidal waves. For a clean day, one sinusoidal function is sufficient for a reasonable accuracy [27], while for a hot summer day, two sinusoidal functions may be required to improve the accuracy [28–30]. Considering that the yearly temperature variation also follows a sinusoidal wave [31], the surface temperature can be modeled by Eq. (8):

$$T_s(t) = A_d\cos(\omega t - \varphi_d) + A_h cos(2\omega t - \varphi_h) + A_y cos\left(\frac{\omega}{365}t - \varphi_y\right) \tag{8}$$

where ω (rad) is the angular frequency, $\omega = 2\pi/(24 \times 3600)$; φ_d, φ_h and φ_y are the phases (in rad) of a day, a half day, and a year; A_d (°C), A_h (°C), and A_y (°C) are the temperature amplitudes of a day, a half day, and a year, respectively.

Considering a negligible heat flux from the deeper ground and assuming the pavement and its underlying layers are uniform, one gets the analytic solution of a pavement temperature by substituting Eq. (8) to Eq. (3):

$$T(z,t) = A_d e^{-\lambda_1 z} cos(\omega t - \lambda_1 z - \varphi_d) + A_h e^{-\lambda_2 z} cos(2\omega t - \lambda_2 z - \varphi_h) + A_y e^{-\lambda_1 z} cos(\omega t/365 - \lambda_3 z - \varphi_y) \tag{9}$$

where $\lambda_1 = \sqrt{\omega/2\alpha}$; $\lambda_2 = \sqrt{2\omega/2\alpha}$; $\lambda_3 = \sqrt{\omega/(2\times 365\alpha)}$ and $\alpha = k/c\rho$ (m^2/s) is the thermal diffusivity.

Taking the partial derivative of $T(z,t)$ with respect to z at $z = 0$ and noting $\cos\varphi - \sin\varphi = \sqrt{2}\cos(\varphi + \pi/4)$, one gets

$$G = A_d P\sqrt{\omega}\cos\left(\omega t - \varphi_d + \frac{\pi}{4}\right) + \sqrt{2}A_h P\sqrt{\omega}\cos\left(2\omega t - \varphi_h + \frac{\pi}{4}\right) + 0.0523PA_y\sqrt{\omega}\cos\left(\frac{\omega}{365}t - \varphi_y + \frac{\pi}{4}\right) \tag{10}$$

where $0.0523 = 1/\sqrt{365}$ and $P = \sqrt{kc\rho}$ is the thermal inertia of the pavement

In Eq. (10), the diurnal temperature amplitude is the primary oscillation while the other terms are relatively small because the amplitudes of Fourier series decay exponentially. For simplicity, G can be set as

$$G = G_0\cos\left(\omega t - \varphi_d + \frac{\pi}{4}\right) + C \tag{11}$$

where G_0 (W/m^2) is the amplitude of the thermal conduction, C (W/m^2) is a regressed constant for the summation of the last two terms at the right-hand side of Eq. (10). Comparing Eq. (11) with Eq. (10), one gets:

$$A_d = \frac{G_o}{P\sqrt{\omega}} + A_0 \tag{12}$$

where A_0 (°C) is a regressed constant characterizing both the deviation of G from the sinusoidal wave and the seasonal energy storage. It may be a function of the air temperature, the air relative humidity and the surface emissivity.

Eq. (12) correlates the variation of the pavement surface temperature to the amplitude of the thermal conduction. In practice, the conduction is hard to be known but the solar absorption is measurable. So, it is advisable to replace the thermal conduction with the solar absorption. According to the hysteresis effect of the energy budget at the ground surface, the thermal conduction G obeys [12,32,33]

$$G = a_1 R_n + a_2\frac{\partial R_n}{\partial t} + a_3 \tag{13}$$

where a_1, a_2 (hr) and a_3 (W/m^2) are regressed constants. a_1 stands for the ratio of the net radiation to the thermal conduction. a_2 is the hysteresis of the surface energy storage; R_n is the net all-wave radiation:

$$R_n = (1-R)I - L \tag{14}$$