Applied Thermal Engineering 113 (2017) 739–748

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Analytical approach for evaluating temperature field of thermal modified asphalt pavement and urban heat island effect

Jiaqi Chen [a,b], Hao Wang [b,*], Hongzhou Zhu [c]

[a] Dept. of Civil Engineering, Central South University, Changsha, Hunan 410075, China
[b] Department of Civil and Environmental Engineering, Rutgers, The State University of New Jersey, Piscataway, NJ 08854, USA
[c] Dept. of Civil Engineering, Chongqing Jiaotong University, Chongqing 400074, China

HIGHLIGHTS

- Derive an analytical approach to predict temperature fields of multi-layered asphalt pavement based on Green's function.
- Analyze the effects of thermal modifications on heat output from pavement to near-surface environment.
- Evaluate pavement solutions for reducing urban heat island (UHI) effect.

ARTICLE INFO

Article history:
Received 29 June 2016
Revised 9 November 2016
Accepted 10 November 2016
Available online 11 November 2016

Keywords:
Near-surface environment
Asphalt pavement
Thermal properties
Temperature fields
Urban heat island

ABSTRACT

This paper aims to present an analytical approach to predict temperature fields in asphalt pavement and evaluate the effects of thermal modification on near-surface environment for urban heat island (UHI) effect. The analytical solution of temperature fields in the multi-layered pavement structure was derived with the Green's function method, using climatic factors including solar radiation, wind velocity, and air temperature as input parameters. The temperature solutions were validated with an outdoor field experiment. By using the proposed analytical solution, temperature fields in the pavement with different pavement surface albedo, thermal conductivity, and layer combinations were analyzed. Heat output from pavement surface to the near-surface environment was studied as an indicator of pavement contribution to UHI effect. The analysis results show that increasing pavement surface albedo could decrease pavement temperature at various depths, and increase heat output intensity in the daytime but decrease heat output intensity in the nighttime. Using reflective pavement to mitigate UHI may be effective for an open street but become ineffective for the street surrounded by high buildings. On the other hand, high-conductivity pavement could alleviate the UHI effect in the daytime for both the open street and the street surrounded by high buildings. Among different combinations of thermal-modified asphalt mixtures, the layer combination of high-conductivity surface course and base course could reduce the maximum heat output intensity and alleviate the UHI effect most.

1. Introduction

With the rapid urbanization, the ground surface in the urban areas is largely replaced with pavements and buildings. Due to the lower albedo and higher heat storage capacity, the temperature of pavement is usually higher than the temperature of ground covered by vegetation or natural soil [1,2]. With the increasing pavement surface temperature, the near-surface air temperature is heated and causes Urban Heat Island (UHI) [3–5].

In order to evaluate the effect of pavement on the UHI effect, accurate pavement temperature fields especially pavement surface temperature need to be known. Currently, temperature fields in the pavement are usually determined by empirical, numerical, or analytical models. The empirical models are usually regression equations that provide a convenient and efficient way to predict pavement temperature [6–9]. However, since the regression models are developed based on a specific database, the model accuracy depends on the regression factors used in the equation and may be inaccurate in some situations.

In the numerical models, complex heat transfer processes can be considered so that these models can be universally used for predicting pavement temperature at different conditions. Most of the

* Corresponding author.
E-mail address: hwang.cee@rutgers.edu (H. Wang).

http://dx.doi.org/10.1016/j.applthermaleng.2016.11.080
1359-4311/

current numerical models are based on either finite element [10–13] or finite difference method [14,15]. In these numerical models, pavement structures are discretized into elements for solving governing equations. The calculation accuracy and computation time of numerical models are highly dependent on mesh density and the total number of elements in the model.

Different from the regression equations and numerical models, analytical models can be used to obtain the rigorous solutions of pavement temperature fields with appropriate assumptions. One advantage of analytical models is that the solutions can be obtained very fast so it can be used instantaneously with real-time applications. The analytical solutions of pavement temperature are usually obtained by solving the initial boundary value problem (IBVP) of heat conduction. Some analytical models use pavement surface temperature as the boundary condition to simplify the problem [16–18]. However, with this simplification the effects of climatic factors such as solar radiation, wind velocity, and air temperature on pavement temperature cannot be analyzed. Therefore, analytical models were developed to consider the above factors with more complex boundaries [19–21]

The high temperature in the asphalt pavement may aggravate pavement deterioration and the UHI effect. In order to reduce pavement temperature, different thermal modification methods have been used, such as increasing surface albedo and modifying thermal conductivities of pavement materials [22–25]. In order to evaluate the effects of thermal modification methods on pavement temperature and the UHI effect using temperature prediction models, pavement structure should be treated as a multi-layer system with heat exchange to the near-surface environment.

2. Objective

In this paper, analytical solutions of temperature fields in the multi-layered asphalt pavement were derived by using the Green's function method that considers heat transfer process within pavement structure and thermal interaction between pavement surface and near-surface environment. The derived models were used to calculate the temperature fields in the pavement and the heat output form pavement surface. The effects of pavement albedo, thermal conductivity, and layer combination on pavement temperature fields and the UHI effect were investigated.

3. Pavement temperature prediction through Green's function

3.1. Heat transfer model of multi-layered pavement structure

The pavement structure is regarded as a multi-layered system with perfect thermal contact, which exchanges heat with the environment at the pavement surface through radiation and convection, as shown in Fig. 1. The temperature at the model bottom is supposed to be constant as long as the pavement structure is thick enough [14].

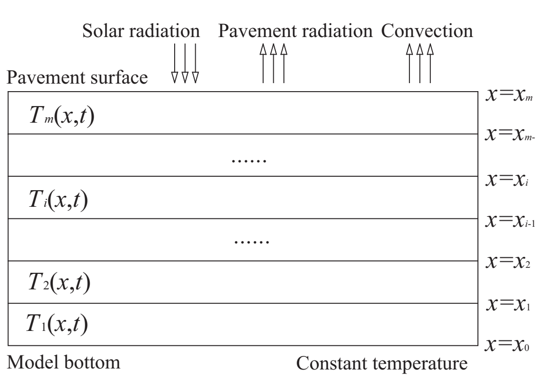

Fig. 1. Schematic diagram of heat transfer in the multi-layered pavement structure.

As shown in Fig. 1, there are two major radiation heat transfer modes between the pavement and the environment, including solar radiation and pavement radiation. Only a portion of the total solar radiation can be absorbed by the pavement and the rest is reflected to the sky. At the same time, the pavement emits thermal radiation to the environment spontaneously. When the pavement structure is not shaded by clouds or surrounding buildings, the net radiation heat flux into the pavement can be calculated using Eq. (1)

$$Q = (1 - \tilde{\alpha})Q_s - \varepsilon\sigma(T_s^4 - T_{sky}^4) \tag{1}$$

where Q is the net radiation heat flux into the pavement (W m^{-2}); Q_s is the total solar radiation that reaches the pavement surface (W m^{-2}); $\tilde{\alpha}$ is pavement surface albedo; ε is pavement emissivity; σ is Stefan–Boltzmann constant, 5.67×10^{-8}W m^{-2} K^{-4}; T_s is pavement surface temperature (K); T_{sky} is the sky temperature (K).

The fourth order terms in Eq. (1) increase the difficulty to derive the analytical solution of pavement temperature. In order to alleviate this difficulty, in this paper, the pavement irradiation is taken into account by reducing the absorbed solar radiation by a factor of 1/3, based on the previous literature [21,26]. Therefore, Eq. (1) is converted to Eq. (2):

$$Q = \frac{2}{3}(1 - \tilde{\alpha})Q_s \tag{2}$$

The outgoing heat flux from the pavement surface through convection can be calculated as Eq. (3):

$$Q_c = h_c(T_s - T_a) \tag{3}$$

where Q_c is outgoing heat flux through convection (W m^{-2}); h_c is convection coefficient (W m^{-2} K^{-1}); T_a is the air temperature (K).

3.2. Analytical solution of pavement temperature fields

The Green's function method is a convenient method to solve complex heat conduction problem in the multi-layer system. Assuming that there is no heat loss between the adjacent layers, the governing equation of the heat transfer problem in Fig. 1 is given as:

$$\alpha_i \frac{\partial^2 T_i(x,t)}{\partial x^2} = \frac{\partial T_i(x,t)}{\partial t} \quad x_{i-1} < x < x_i, \quad t > 0 \tag{4}$$

where $T_i(x,t)$ is the temperature field in the i-th layer (°C); x is spatial coordinate (m); t is time (s); α_i is the diffusivity of the i-th layer (m^2 s^{-1}).

The boundary conditions of Eq. (4) are given as:

$$T_1(x,t)|_{x=x_0} = f_1(t) \tag{5-a}$$

$$T_i(x,t)|_{x=x_i} = T_{i+1}(x,t)|_{x=x_i} \tag{5-b}$$

$$k_i \frac{\partial T_i(x,t)}{\partial x}|_{x=x_i} = k_{i+1} \frac{\partial T_{i+1}(x,t)}{\partial x}|_{x=x_i} \tag{5-c}$$

$$k_m \frac{\partial T_m(x,t)}{\partial x}|_{x=x_m} + h_c T_m(x,t)|_{x=x_m} = h_c f_2(t) \tag{5-d}$$

where k_i is the thermal conductivity of the i-th layer (W m^{-1} K^{-1}); $f_1(t)$ is the pavement temperature at x = x0 (°C); $f_1(t)$ reflects the combined effect of radiation and convection at pavement surface, and can be expressed as:

$$f_2(t) = \frac{Q(t)}{h_c} + T_a(t) \tag{6}$$

The initial condition of Eq. (4) is given as: