Fluid-solid Coupling Simulation of Pavement and Near-surface and Sensitivity Analysis on Near-surface Temperature

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Abstract

In this paper, a three-dimensional fluid-solid coupling model of asphalt pavement and near surface is established by finite element method based on fluid-solid coupling theory. The validity of the model and the reliability of the simulation data are verified by the measured data. By controlling single variable to change the thermal parameters (thermal conductivity, specific heat, emissivity, reflectance, density and slope A of convection coefficient) of pavement surface and meteorological factors (wind speed and solar radiation), the temperature distribution of pavement structure layer and near surface temperature during high temperature period in daytime and low temperature period in night were studied. The positive and negative correlation between the change of temperature field and the change of various factors is obtained, and the specific measures to alleviate the near-surface thermal environment, reduce the urban heat island effect and enhance the thermal comfort of pedestrians are put forward. Through orthogonal test, the sensitivity order of pavement properties to near-surface temperature and pavement temperature in daytime high temperature period is obtained (reflectivity > slope A > emissivity > conductivity > density > specific heat). It is of great guiding significance to further improve the accuracy of predictive three-dimensional fluid-structure coupling model and to reasonably select pavement material parameters.

KEYWORDS: Fluid-Solid Coupling; Finite Element Method; Near-surface air temperature; sensitivity analysis; Orthogonal Test
1 Introduction

Urban Heat Island means higher urban temperatures in urban areas than in surrounding suburbs and rural areas. The urban environment is related to positive thermal equilibrium. For instance, high absorption of solar radiation and man-made heat, and reduced heat loss all can cause it. (And and Bunce, 2001). Some high-density cities have regional and temporal variability, and heat island intensity may exceed several degrees. (MatSantamouris, 2007; Pauleit et al., 2012)(Giannopoulou et al., 2011). Global climate change is an important reason for the significant increase of urban temperature in high-density and anthropized urban areas. (Asimakopoulos et al., 2012; DimitraFounda, 2011; Hu et al., 2018; Livada et al., 2007; Wypych et al., 2018)(Mathai and Haubold, 2018). Amplify extreme environment is facing various dangerous events, which determines the global average overheating of small-scale growth of urban heat island effect, and is aggravated by heat waves(Grimm et al., 2008). Especially in highly anthropized cities, it is more likely to lead to microclimate characterized by heat discomfort, and even to thermal health problems(Michelozzi et al., 2005).

To mitigate the urban heat island effect, in addition to the use of green space, proper landscaping and design of urban greening modules (ChenYu and WongNykHien, 2009) (Xiang et al., 2018; Zoulia et al., 2009), proper shading and solar control of urban surfaces(Akbari, 2002; Akbari et al., 2001; Karunarathna et al., 2017) appropriate radiators are used to emit excessive environmental heat involving the use of ground, ambient air and water. Low temperature (Geros et al., 2005; Kusaka et al., 2001; Santamouris et al., 2010), and the use of low-temperature urban buildings in the bottom roof are reliable schemes (Santamouris, 2014)(Niachou et al., 2001; Santamouris et al., 2007; Sfakianaki et al., 2010; Synnefa and Santamouris, 2012; Takebayashi and Moriyama, 2007; Theodosiou, 2009; Zinzi, 2010). Consciously select urban pavement materials (Salata et al., 2015), develop and consciously use cooling materials with high reflectivity, high thermal emissivity, which can amortize and dissipate solar and thermal energy, and intelligent materials with high optical and thermal properties (Kolokotsa et al., 2012; Synnefa et al., 2012, 2008, 2007); Controlling the urban heat island effect, while controlling the energy consumption of buildings (Evangelisti et al., 2014; Pisello et al., 2016; Rosso et al., 2014) is extremely important.

Decreasing the pavement surface temperature may contribute highly to improve the thermal conditions in cities suffering from heat island effect. Many recent studies have done on that pavement play a significant role on the overall urban thermal equilibrium (Gaitani et al., 2007; Menon et al., 2010; Rosenzweig et al., 2009). The choice of urban materials is based on: thermal capacity (the ability to control the storage and release of solar energy with a certain time offset); radiation heat transfer coefficient of wavelength (optimizing radiation exchange according to solar radiation and surrounding environment); which will have an impact on the thermal comfort of urban outdoor space (Flimel and Dušáková, 2018; Livada et al., 2002; Taler, 2019), and these cities can avoid affecting population and their health through control. High thermal stress (D’Ippoliti et al., 2010; Kovats and Kristie, 2006).

This paper aims to select proper parameters for urban pavements to mitigate the urban heat island effect by simulating temperature of pavement and near-surface air and analysis the importance order of parameters

2 DEVELOPMENT AND VALIDATION OF THREE-DIMENSIONAL FLUID-SOLID COUPLING FINITE ELEMENT MODEL

2.1 Fundamental principles

The main basis for the theoretical prediction method of asphalt pavement temperature field is heat transfer theory. The general expression of the temperature field of asphalt pavement is \( t = f(x, y, z, i) \). To determine its size, we must first find the differential equation
describing the formula. According to Fourier's law and energy conservation and transformation law, the temperature of each point in the object can be correlated to establish a general differential equation of temperature field—thermal differential equation.

It is assumed that the object is an isotropic continuous medium with a thermal conductivity of $\lambda$, a specific heat capacity of $c$ and a density of $\rho$. It is assumed that the object has an internal heat source and its heat intensity per unit volume per unit time is $q_r$ (W/m$^3$). A microelement $\mathrm{dv} = \mathrm{dxdydz}$ is separated from the object conducting the heat. According to the law of energy transformation and conservation, the thermal equilibrium of the microelement is analyzed. The heat imported and exported in the time of $\mathrm{d}\tau$, together with the heat generated by the internal heat source, is equal to the increase of the thermal energy of the microelement body.

![Figure 1: Thermal Conduction of Microelements](image)

The net heat of the imported and exported microelement can be obtained by adding the net heat of the imported and exported microelement in the direction of $x$, $y$ and $Z$. In the time of $\mathrm{d}\tau$, the heat introduced along the X-Plane can be recorded as $d\Phi_x = q_x \mathrm{dxdydz} \mathrm{d}\tau$. The heat derived from the surface of $x + \mathrm{d}x$ is $d\Phi_x = q_{x+d} \mathrm{dxdydz} \mathrm{d}\tau$, while $q_{x+dx} = q_x + \frac{\partial q_x}{\partial x} \mathrm{dx}$. In the time of $\mathrm{d}\tau$, the net heat introduced and derived from the microelement along the X-axis is:

$$d\Phi_x - d\Phi_x = -\frac{\partial q_x}{\partial x} \mathrm{dxdydz} \mathrm{d}\tau \quad (1)$$

Similarly, in the time of $\mathrm{d}y$ and $\mathrm{d}z$, the net heat imported and derived along the Y and Z-axis is respectively:

$$d\Phi_y - d\Phi_y = -\frac{\partial q_y}{\partial y} \mathrm{dxdydz} \mathrm{d}\tau \quad (2)$$
$$d\Phi_z - d\Phi_z = -\frac{\partial q_z}{\partial z} \mathrm{dxdydz} \mathrm{d}\tau \quad (3)$$

The following formula can be obtained by adding the heat imported and exported from three directions:

$$I = -\left(\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z}\right) \mathrm{dxdydz} \mathrm{d}\tau \quad (4)$$

Since $q_x = -\lambda \frac{\partial t}{\partial x}$, $q_y = -\lambda \frac{\partial t}{\partial y}$, $q_z = -\lambda \frac{\partial t}{\partial z}$, the following formulas can be obtained:

$$I = \left[\left(\frac{\partial}{\partial x} (\lambda \frac{\partial t}{\partial x}) + \frac{\partial}{\partial y} (\lambda \frac{\partial t}{\partial y}) + \frac{\partial}{\partial z} (\lambda \frac{\partial t}{\partial z})\right) \mathrm{dxdydz} \mathrm{d}\tau \right] \quad (5)$$
In the $dt\tau$ time, the caloric value of the heat source in the microcellular body is as follows:

$$II = q_r \, dx \, dy \, dz \, dt\tau$$

In the time of $dt\tau$, the increment of thermodynamic energy of microelement is $III = \rho c \frac{\partial t}{\partial\tau} \, q_r \, dx \, dy \, dz \, dt\tau$. According to the law of conservation of energy, the following formula can be obtained:

$$\rho c \frac{\partial t}{\partial\tau} = \frac{\partial}{\partial x} (\lambda \frac{\partial t}{\partial x}) + \frac{\partial}{\partial y} (\lambda \frac{\partial t}{\partial y}) + \frac{\partial}{\partial z} (\lambda \frac{\partial t}{\partial z}) + q_v$$

When the thermal conductivity is constant, the above formula can be simplified as follows:

$$\frac{\partial t}{\partial\tau} = \frac{\lambda}{\rho c} \frac{\partial^2 t}{\partial x^2} + \frac{\partial^2 t}{\partial y^2} + \frac{\partial^2 t}{\partial z^2} + \frac{q_v}{\rho c}$$

(6)

(7)

In practical application, the expression of $\frac{1}{\rho c}$ is replaced by $\alpha$, $\alpha$ is micro-thermal diffusivity, indicating the ability of the temperature field of each part of the object to converge when it is heated and cooled. The unit is m²/s.

The key point of fluid-solid coupling calculation is to establish the mathematical description equation of heat transfer at the interface between fluid and solid, and to describe the heat absorbed by the side of the body. According to the law of conservation of energy, the heat released from the solid side is equal to the flow energy. The following equation can be obtained by combining the Fourier heat transfer equation with the governing equation of fluid convection heat transfer:

$$K_{\text{cond}} \frac{\partial T}{\partial n_{w\text{f}}} = q_{\text{conv}} = h_{\text{conv}} (T_f - T_w)$$

(8)

Where, $K_{\text{cond}}$ is Thermal conductivity of solids; $q_{\text{conv}}$ is the Local heat transfer; $h_{\text{conv}}$ is the local convection heat transfer coefficient; $T_f$ is the Fluid temperature; $T_w$ is the Wall temperature.

In this paper, the third boundary condition is used to calculate the fluid-solid coupling heat transfer between pavement and near surface air.

### 2.2 Basic Conditions and Hypothesis

Asphalt pavement is in the atmospheric environment, its temperature field will be affected by various external factors. The atmospheric environment exchanges heat energy with the asphalt pavement surface, forming the photothermal environment of asphalt pavement. In the photothermal environment, the asphalt pavement and the external environment exchange heat.

In order to facilitate the calculation and analysis of the temperature field of urban pavement and near-surface, the following assumptions are made for the pavement and near-surface model by using the finite element method:

1. All structural layers of asphalt pavement are isotropic;
2. There is no void between different layers of pavement structure. It is assumed that the contact state between layers is good, and the influence of thermal resistance between layers is not considered;
3. When choosing the thermal physical parameters of pavement materials and near-surface air layer, the thermal physical parameters of each layer structure are selected as a fixed value without considering the effect of temperature variation;
4. The change period of pavement structure temperature is 24 hours.

2.3 The structure and model of model

(1) Pavement structure and integrated local modeling

In this chapter, a typical pavement structure is selected to simulate the temperature field. A simplified global local model is used to analyze the heat transfer between pavement and near surface air. The whole local model includes pavement structure (asphalt layer, base and soil foundation) and near surface air (air 2 m away from road surface). The geometric model is shown in Figure 2. The finite element model corresponding to the outdoor asphalt mixture model is established by using DC3D8 element in Abaqus. The model size is 7m x 3.75m x 3.0m (pavement part). The air fluid model is built by CFD module. The model size is 7m x 3.75m x 2.0m (air part, upper part of the model).
Figure 2: Integrated modeling for temperature simulation

(2) Thermal property parameters and climate condition

Table 1 Temperature simulation parameters of a certain place in Xi'an, Shanxi

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Air</th>
<th>Asphalt Concrete</th>
<th>Aggregate Base</th>
<th>Subgrade</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Conductivity K ( [J \cdot h \cdot m \cdot ^\circ C \cdot ^{-1}] )</td>
<td>9.25</td>
<td>4680</td>
<td>5616</td>
<td>5616</td>
</tr>
<tr>
<td>Density ( \rho / (kg \cdot m \cdot ^{-3}) )</td>
<td>1.184</td>
<td>2350</td>
<td>2200</td>
<td>1800</td>
</tr>
<tr>
<td>Specific Heat Capacity ( c ) ( [J \cdot (kg \cdot ^\circ C) \cdot ^{-1}] )</td>
<td>1004</td>
<td>950</td>
<td>911.7</td>
<td>1040</td>
</tr>
<tr>
<td>Surface Solar Radiation Absorptivity ( \alpha_s )</td>
<td>0.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal Emissivity ( \varepsilon )</td>
<td>0.81</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat Convection Coefficient ( hc ) ( [J \cdot (h \cdot m^2 \cdot ) \cdot ^{-1}] )</td>
<td>( hc=3600(3.7v+9.4) ), (v, wind velocity, m/s)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Absolute Zero TZ ( [^\circ C] )</td>
<td>-273</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stefan-Boltzmann Constant ( \sigma \cdot [j \cdot (h \cdot m^2 \cdot k4)] )</td>
<td>( 2.041092 \times 10^{-4} )</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Hot Summer Climate Data in Hot Region of Xian, Shanxi

<table>
<thead>
<tr>
<th>Month</th>
<th>Daily peak air temperature ( T_{a}^{\max} )</th>
<th>Daily lowest air temperature ( T_{a}^{\min} )</th>
<th>Daily total solar radiation volume ( Q ) ( [MJ/m^2] )</th>
<th>Daily effective sunlight hour ( c ) ( [h] )</th>
<th>Daily average wind velocity ( V ) ( [m/s] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>August</td>
<td>39</td>
<td>26</td>
<td>24.68</td>
<td>9.58</td>
<td>1.8</td>
</tr>
</tbody>
</table>

(3) Initial and boundary conditions
The initial condition: The whole model is set to the predefined temperature field of 25 C.
The boundary condition: The boundary conditions of the simplified heat transfer model include:
the solar radiation heat flux on the road surface; the surface convection between the road surface and
the air; the surface radiation of the road surface and the temperature boundary of the air near the surface.
For "air temperature and convective heat exchange" and "effective radiation on pavement", it is defined
in the Interaction module of ABAQUS/CAE and the solar radiation in the Step module. The ambient
air temperature is set as the temperature boundary at the upper boundary height of 2m near the surface
air. All other boundary conditions are assumed to be adiabatic.

The ambient temperature uses a linear combination of two sinusoidal functions to simulate the
daily variation of temperature, and the results are in good agreement with the actual situation.

\[ T_n = \bar{T}_a + T_m [0.96 \sin \omega (t - t_0) + 0.14 \sin 2\omega (t - t_0)] \]  

(9)

Where \( \bar{T}_a \) is average temperature, °C, \( \bar{T}_a = \frac{1}{2} (T_a^{\text{max}} + T_a^{\text{min}}) \);
\( T_m \) is the daily temperature change range, °C, \( T_m = \frac{1}{2} (T_a^{\text{max}} - T_a^{\text{min}}) \), \( T_a^{\text{max}} \), \( T_a^{\text{min}} \) are the daily maximum and minimum temperatures, °C;
\( t_0 \) is the initial phase, and the difference between the maximum solar radiation and
the maximum temperature is increased by 7h. In general, the time difference is 2h. For
this reason, \( t_0 = 9 \) can be taken; in calculation, t is measured in hours.

(4) User subroutine addition

"Temperature and convective heat exchange" and "solar radiation" are added to the
model in the subroutine. The solar radiation heat flux defined by the user subroutine
deflux ( ) in Abaqus® varies in one day. Surface temperature convection exchange is a
function of ambient air temperature with time and convection coefficient with wind
speed. It is defined by the user subroutine film ( ) in Abaqus®. Effective surface radiation
is defined directly by using the keyword * surface radiate in Abaqus® and radiates to the
ambient atmosphere through the surface.

According to the results of Barber’s study, the diurnal variation process of solar
radiation \( q (t) \) can be approximately represented by the following functions:

(5) Analysis step setup and definition of contact

The model simulates the temperature distribution of pavement and air for 24 hours,
with a fixed step length of 0.5 hours and a total of 49 steps. In the model, the contact
between asphalt pavement and air is defined as fluid-solid coupling contact. The links
between different layers of pavement use Tie links in the interaction as a whole.

2.3 Validation of Integrated Local Modeling

In this chapter, the model is validated by field data. The pavement temperature is measured and
simulated, which is validated at three locations of 0.6m and 1.1m on the pavement.
Figure 3: Weather data for the sunny days in summer

Figure 4: Comparison of measured and simulated pavement temperature at different heights

Figure 4 shows the comparison between simulation results and measured results of asphalt pavement. It can be seen the overall trend of the calculated value is consistent with the measured value. The maximum difference between the calculated and measured pavement temperature in the model is 2.9 °C, and the error is less than 10%. This shows that the model can be used to simulate the temperature of different asphalt pavement and near surface under different weather conditions. The existence of errors is related to many factors, such as simplification of models and assumption of parameters. Especially when calculating the convective heat transfer process, the daily temperature is assumed to change according to the double sinusoidal law; when calculating the short-wave radiation of the sun, the radiation intensity changes approximately in the form of cosine, but in the actual situation, the two are greatly affected by the meteorological factors around the road surface, such as cloud amount, the irregular change of the daily temperature and so on.

3 SIMULATION BASED SENSITIVITY ANALYSIS USING THE SIMPLIFIED MODEL

In this chapter, the three-dimensional finite element fluid-solid coupling model is used to study the temperature field of asphalt pavement and near surface. The influence of thermal parameters and meteorological data of pavement materials on the temperature field distribution is discussed, and the sensitivity analysis of single factor is carried out. In sensitivity analysis, other factors remain constant
and only one factor is changed. The temperature distribution along the depth of pavement and near-surface air were extracted at the two time points, and the effects of various factors on daytime high temperature and night low temperature were analyzed in detail.

3.1 Thermal conductivity

![Figure 5: Sensitive correlation between temperature and Thermal conductivity](image)

The heat exchange between the pavement and near-surface air is through heat conduction. During the high temperature period in the daytime, with the increase of thermal conductivity, the air temperature near the surface decreases gradually, which increases the heat flow of air into the pavement layer, and the corresponding temperature in the pavement structure increases gradually, and accelerates the heat flow into the deep pavement structure layer. In the low temperature period at night, with the increase of thermal conductivity, the air temperature near the surface increases gradually, which increases the heat flow from the pavement layer to the air, and the temperature in the corresponding pavement structure decreases gradually. The increase of thermal conductivity of pavement surface promotes heat flow from air to deep pavement. This effectively ensures that the near surface temperature will not be too high in the daytime high temperature period and too low in the night low temperature period. Heat is more easily transmitted to the deep structure layer of the pavement, resulting in a higher temperature in the deep layer of the pavement, which will alleviate the temperature of the upper layer of the pavement.
3.2 Specific heat

Specific heat capacity is a thermophysical parameter to measure the relative magnitude of heat conduction capacity and heat storage capacity of materials. Materials with large specific heat capacity react quickly to the change of their thermal environment, while materials with small specific heat capacity react slowly, and it takes a long time to achieve a new equilibrium environment. During the high temperature period in the daytime, with the increase of specific heat capacity, the temperature of near-surface air decreases gradually, and the temperature in the pavement structure also decreases gradually. In the low temperature period at night, with the increase of specific heat capacity, the temperature of near-surface air gradually increases, the temperature of upper pavement layers increases, and then the temperature of the deep pavement layers decreases.

3.3 Thermal Emissivity
Figure 7: Sensitive correlation between temperature and Thermal emissivity

During the high temperature period in the daytime, with the increase of thermal emissivity, the temperature of pavement and near-surface air decreases, and more thermal energy is emitted/radiated to near-surface air, and then to the whole ambient atmosphere. The influence of thermal emissivity on surface temperature of pavement is greater than that on near surface air temperature. However, in the low temperature period at night, with the increase of thermal emissivity, the temperature of pavement and near-surface air decreases. The analysis shows that the use of high thermal emissivity materials can reduce the temperature of air on the surface and near the surface of the pavement, thus making the pavement cooler. But this will have a negative impact on building energy consumption at night or in winter and in cold areas. It is very difficult to change the thermal emissivity of pavement materials effectively.
3.4 Thermal Reflectance

Figure 8: Sensitive correlation between temperature and Thermal reflectance

With the increase of solar reflectance (1-absorptivity), the temperature of pavement structure layer and near-surface air both decrease in high temperature period during daytime, and the change of near-surface air temperature is more significant, and the solar energy absorbed by pavement is less, which primarily because the pavement absorbs less solar energy. In addition, the temperature of pavement and near-surface air decreases more obviously in the daytime high temperature period than in the night low temperature period, especially in the pavement surface temperature. When the solar reflectivity increases from 0.1 to 0.5, the maximum temperature of pavement decreases by 12 ℃ (from 61 ℃ to 49 ℃) in the daytime high temperature period, while the temperature of pavement decreases slightly in the night low temperature period. Taking the temperature of 0.6m near the surface as an example, the daytime high temperature decreases by 7 ℃ (from 47 ℃ to 40 ℃) as the solar radiation reflectance increases from 0.1 to 0.5. However, the temperature change at 0.6m during the night low temperature period is only about 2 ℃.
3.5 Density

The mechanism of the influence of density change on pavement temperature and near-surface temperature is that more heat is needed to achieve energy balance with the increase of total pavement quality. It can be seen from the graph that with the increase of pavement surface density, the surface temperature and the temperature in pavement structure layer decrease in daytime high temperature period, and rise in night low temperature period near surface temperature and the temperature in pavement structure layer. But the impact is not very big. Using high density pavement materials can mitigate the urban heat island effect appropriately, but the effect is not significant.

Figure 9: Sensitive correlation between temperature and Density
3.6 Slope A of Convection Coefficient

Convective coefficient is very important for heat transfer of pavement and near surface air layer, which is not only related to the air convection velocity near pavement, but also to the surface smoothness of pavement. During the daytime high temperature period, with the increase of slope A of convection coefficient, the temperature of near surface and upper structure layer of pavement decreases, while the temperature of deep structure layer of pavement increases. During the low temperature period at night, with the increase of slope A of convection coefficient, the same near surface temperature and the temperature of the upper structure layer of the pavement decrease, while the temperature of the deep structure layer of the pavement increases. The daytime high temperature of pavement surface drops about by 4 °C (from 60 °C to 56 °C) as the slope of convection coefficient increases from 2.2 to 5.2, compared with a drop of about 2 °C (from 47 °C to 45 °C) for the near-surface air temperature at 0.6m height.

Figure 10: Sensitive correlation between temperature and Slope A
3.7 Wind Speed

Wind speed and the slope A of convection coefficient have the similar effect of on the temperature near the pavement surface. Increasing wind speed will enhance the convection between pavement and air, thus reducing pavement temperature. During the daytime high temperature period, with the increase of wind speed, the temperature of near surface and upper structure layer of pavement decreases, while the temperature of deep structure layer of pavement increases. During the low temperature period at night, with the increase of wind speed, the same near surface temperature and the temperature of the upper structure layer of the pavement decrease, while the temperature of the deep structure layer of the pavement increases. Strengthen natural ventilation in urban central area can reduce the temperature of pavement and near surface air, and enhance the thermal comfort of pedestrians. Higher convection coefficient corresponds to lower pavement temperature and near surface air temperature. The higher the wind speed near the surface, the more heat energy is transferred to the surrounding atmosphere through convection.
3.8 Solar radiation

Solar radiation is one of the most important factors affecting the thermal environment of pavement and near surface, especially during the high temperature period in the daytime. With the increase of solar radiation, the surface temperature and pavement structure layer temperature increase during daytime and night. When the solar radiation decreases from 40 MJ/m² to 10 MJ/m², the surface temperature decreases by 27°C (from 71°C to 44°C), compared with a drop of about 15 °C (from 53°C to 38°C) for the near-surface air temperature at 0.6m height during the high temperature period during the day. This shows that the pavement and near-surface temperature can be effectively reduced and the near-surface thermal environment can be improved by shielding solar radiation (such as roadside buildings, photovoltaic panels, tree planting, etc.).

4 Sensitivity Analysis Using Orthogonal Test

4.1 Selection of parameters

The temperature field of the three-dimensional fluid-solid coupling model of pavement and near surface is taken as the research area, and the corresponding parameters of the model are given to the pavement and near surface. The model is clear and the boundary conditions are not very complicated. Therefore, six parameters (thermal conductivity, thermal emissivity, specific heat, reflectivity, density and slope A of convection coefficient) of asphalt pavement surface material are selected for analysis. Meteorological conditions such as wind speed and solar radiation are not analyzed here.
4.2 Parameter Level Settings

Thermal conductivity, thermal emissivity, specific heat, reflectivity, density and slope A of convection coefficient are set to five levels, which expressed in 1, 2, 3, 4 and 5, respectively. The level classification of specific parameters and the values of each level parameters are as follows.

Table 2 Level Classification of various parameters and level parameter values

<table>
<thead>
<tr>
<th>Level</th>
<th>Conductivity (J·(h·m·℃)^{-1})</th>
<th>Emissivity</th>
<th>Specific heat (J·(kg·℃)^{-1})</th>
<th>reflectivity</th>
<th>Density (kg·m^{-3})</th>
<th>slope A</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.2</td>
<td>0.6</td>
<td>400</td>
<td>0.5</td>
<td>2050</td>
<td>2.3</td>
</tr>
<tr>
<td>2</td>
<td>0.6</td>
<td>0.7</td>
<td>700</td>
<td>0.6</td>
<td>2200</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>0.81</td>
<td>1300</td>
<td>0.7</td>
<td>2350</td>
<td>3.7</td>
</tr>
<tr>
<td>4</td>
<td>1.4</td>
<td>0.9</td>
<td>1900</td>
<td>0.8</td>
<td>2500</td>
<td>4.4</td>
</tr>
<tr>
<td>5</td>
<td>2.2</td>
<td>0.98</td>
<td>2500</td>
<td>0.9</td>
<td>2650</td>
<td>5.1</td>
</tr>
</tbody>
</table>

4.3 Design of Orthogonal Test Table

According to the design principle of orthogonal test table, orthogonal test with six factors and five levels needs 25 times. 25 models need to be built and run with ABAQUS, each model chooses a set of characteristic model parameters. If complete test analysis is carried out, \( 5^6 = 15625 \) tests are required.

The combination of parameters under different schemes is shown in the table below. The maximum temperature at different heights caused by the change of parameters combination is used as the sensitivity index Y under the test scheme.

Table 3 The combination of parameters and sensitivity index Y at different heights

<table>
<thead>
<tr>
<th>Experimental Scheme</th>
<th>Influence Factors</th>
<th>Sensitivity index/Y (Maximum temperature)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>conductivity</td>
<td>emmissivity</td>
</tr>
<tr>
<td>1</td>
<td>0.2</td>
<td>0.6</td>
</tr>
<tr>
<td>2</td>
<td>0.2</td>
<td>0.7</td>
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<tr>
<td>13</td>
<td>1</td>
<td>0.81</td>
</tr>
<tr>
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<td>0.9</td>
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<tr>
<td>15</td>
<td>1</td>
<td>0.98</td>
</tr>
<tr>
<td>16</td>
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<td>0.6</td>
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<td>0.81</td>
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<td>19</td>
<td>1.4</td>
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<tr>
<td>20</td>
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<td>0.98</td>
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<td>0.6</td>
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<td>22</td>
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<td>0.7</td>
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<tr>
<td>23</td>
<td>2.2</td>
<td>0.81</td>
</tr>
</tbody>
</table>
4.4 Study and Analysis of Near-surface Temperature Field

It can be seen from Table 4 that the sensitivity of the six parameters affecting the maximum surface temperature is reflectivity > slope A > emissivity > conductivity > density > specific heat.

Table 4 Sensitivity Comparison of Range Method for Different Parameter Combinations of Surface Maximum Temperature

<table>
<thead>
<tr>
<th>Experimental scheme</th>
<th>Conductivity $J/(h \cdot m \cdot ^\circ C)^{-1}$</th>
<th>emissivity</th>
<th>specific heat $J/(kg \cdot ^\circ C)^{-1}$</th>
<th>reflectivity</th>
<th>Density $kg/m^3$</th>
<th>slope A</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{ij}$</td>
<td>337.97</td>
<td>344.17</td>
<td>335.44</td>
<td>293.88</td>
<td>334.87</td>
<td>350.43</td>
</tr>
<tr>
<td>$K_{2j}$</td>
<td>331.71</td>
<td>336.76</td>
<td>332.54</td>
<td>314.28</td>
<td>333.07</td>
<td>339.79</td>
</tr>
<tr>
<td>$K_{3j}$</td>
<td>332.67</td>
<td>332.27</td>
<td>331.92</td>
<td>332.38</td>
<td>331.18</td>
<td>332.39</td>
</tr>
<tr>
<td>$K_{4j}$</td>
<td>332.55</td>
<td>327.27</td>
<td>332.25</td>
<td>353.23</td>
<td>332.95</td>
<td>324.43</td>
</tr>
<tr>
<td>$K_{5j}$</td>
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<td>325.57</td>
<td>333.90</td>
<td>372.28</td>
<td>333.99</td>
<td>319.02</td>
</tr>
<tr>
<td>Range</td>
<td>6.82</td>
<td>18.60</td>
<td>3.52</td>
<td>78.40</td>
<td>3.68</td>
<td>31.41</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>reflectivity &gt; slope A &gt; emissivity &gt; conductivity &gt; density &gt; specific heat</td>
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<td></td>
</tr>
</tbody>
</table>

It can be seen from Table 5 that the sensitivity of the six parameters affecting the maximum temperature of 0.1m is reflectivity > slope A > emissivity > conductivity > density > specific heat.

Table 5 Sensitivity Comparison of Range Method for Different Parameter Combinations of 0.1m Maximum Temperature

<table>
<thead>
<tr>
<th>Experimental scheme</th>
<th>Conductivity $J/(h \cdot m \cdot ^\circ C)^{-1}$</th>
<th>emissivity</th>
<th>specific heat $J/(kg \cdot ^\circ C)^{-1}$</th>
<th>reflectivity</th>
<th>Density $kg/m^3$</th>
<th>slope A</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{ij}$</td>
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<td>322.24</td>
<td>314.41</td>
<td>277.78</td>
<td>313.99</td>
<td>327.75</td>
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<tr>
<td>$K_{2j}$</td>
<td>311.14</td>
<td>315.60</td>
<td>311.79</td>
<td>295.78</td>
<td>312.35</td>
<td>318.28</td>
</tr>
<tr>
<td>$K_{3j}$</td>
<td>312.01</td>
<td>311.67</td>
<td>311.32</td>
<td>311.72</td>
<td>310.69</td>
<td>311.76</td>
</tr>
<tr>
<td>$K_{4j}$</td>
<td>311.90</td>
<td>307.22</td>
<td>311.69</td>
<td>330.15</td>
<td>312.27</td>
<td>304.72</td>
</tr>
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<td>$K_{5j}$</td>
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<td>305.73</td>
<td>313.25</td>
<td>347.02</td>
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<td>299.95</td>
</tr>
<tr>
<td>Range</td>
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<td>16.51</td>
<td>3.08</td>
<td>69.25</td>
<td>3.30</td>
<td>27.80</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

It can be seen from Table 6 that the sensitivity of the six parameters affecting the maximum temperature of 0.6m is reflectivity > slope A > emissivity > conductivity > density > specific heat.

Table 6 Sensitivity Comparison of Range Method for Different Parameter Combinations of 0.6m Maximum Temperature

<table>
<thead>
<tr>
<th>Experimental scheme</th>
<th>Conductivity $J/(h \cdot m \cdot ^\circ C)^{-1}$</th>
<th>emissivity</th>
<th>specific heat $J/(kg \cdot ^\circ C)^{-1}$</th>
<th>reflectivity</th>
<th>Density $kg/m^3$</th>
<th>slope A</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K_{ij}$</td>
<td>250.34</td>
<td>253.37</td>
<td>248.97</td>
<td>228.24</td>
<td>248.73</td>
<td>256.62</td>
</tr>
<tr>
<td>$K_{2j}$</td>
<td>247.16</td>
<td>249.66</td>
<td>247.52</td>
<td>238.43</td>
<td>247.87</td>
<td>251.25</td>
</tr>
<tr>
<td>$K_{3j}$</td>
<td>247.67</td>
<td>247.48</td>
<td>247.28</td>
<td>247.49</td>
<td>246.90</td>
<td>247.51</td>
</tr>
<tr>
<td>$K_{4j}$</td>
<td>247.60</td>
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<td>247.48</td>
<td>257.97</td>
<td>247.83</td>
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<td>244.19</td>
<td>248.43</td>
<td>267.53</td>
<td>248.35</td>
<td>240.79</td>
</tr>
<tr>
<td>Range</td>
<td>3.44</td>
<td>9.17</td>
<td>1.69</td>
<td>39.29</td>
<td>1.84</td>
<td>15.82</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>reflectivity &gt; slope A &gt; emissivity &gt; conductivity &gt; density &gt; specific heat</td>
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<td></td>
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<td></td>
</tr>
</tbody>
</table>
It can be seen from Table 7 that the sensitivity of the six parameters affecting the maximum temperature of 1.1m is reflectivity > slope A > emissivity > conductivity > density > specific heat.

Table 7 1.1m Sensitivity Comparison of Range Method for Different Parameter Combinations of 1.1m Maximum Temperature

<table>
<thead>
<tr>
<th>Experimental scheme</th>
<th>Conductivity J(h m⁻¹°C⁻¹)</th>
<th>emissivity</th>
<th>specific heat J(kg m⁻³°C⁻¹)</th>
<th>reflectivity</th>
<th>Density kg m⁻³</th>
<th>slope A</th>
</tr>
</thead>
<tbody>
<tr>
<td>K1j</td>
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<td>224.63</td>
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<td>209.34</td>
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</tr>
<tr>
<td>K2j</td>
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<td>222.37</td>
<td>221.11</td>
<td>215.52</td>
<td>221.30</td>
<td>223.38</td>
</tr>
<tr>
<td>K3j</td>
<td>221.17</td>
<td>221.06</td>
<td>220.94</td>
<td>221.06</td>
<td>220.69</td>
<td>221.06</td>
</tr>
<tr>
<td>K4j</td>
<td>221.11</td>
<td>219.54</td>
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<td>227.45</td>
<td>221.26</td>
<td>218.64</td>
</tr>
<tr>
<td>K5j</td>
<td>220.70</td>
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<td>221.57</td>
<td>233.32</td>
<td>221.59</td>
<td>216.97</td>
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<td>2.14</td>
<td>5.55</td>
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<tr>
<td>Sensitivity</td>
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<td></td>
<td></td>
<td></td>
<td>1.08</td>
<td>23.98</td>
</tr>
</tbody>
</table>

In range analysis method, the sensitivity indexes of reflectivity and slope of convective heat transfer coefficient of asphalt pavement surface are larger than specific heat capacity, density, thermal conductivity and emissivity. The thermal conductivity is the most sensitive among the six parameters selected.

5 Conclusions

The three-dimensional fluid-solid coupling model was developed and verified to simulate temperature field for a typical pavement and near-surface integral structure under typical climate in summer in Xi'an, Shaanxi with high temperature. The relationships of eight important variables including pavement parameters and meteorological factors on near-surface temperature were studied respectively. Complicated relationships between these variables and temperature of pavement and near-surface air are shown as below.

In terms of daytime high temperature period, thermal conductivity, specific heat, emissivity, reflectance, density, slope A of convection coefficient of pavement surface and wind speed have negative correlation with near-surface air temperature. While solar radiation has positive correlation with near-surface air temperature. Specific heat, emissivity, reflectance, density, slope A of convection coefficient of pavement surface and wind speed have negative correlation with pavement structure temperature. While thermal conductivity and solar radiation have positive correlation with pavement structure temperature.

In terms of night-time low temperature period, thermal conductivity, specific heat, density of pavement surface and solar radiation have positive correlation with near-surface air temperature. While emissivity, reflectance, slope A of convection coefficient of pavement surface and wind speed have negative correlation with near-surface air temperature. Thermal conductivity, density of pavement surface and solar radiation of pavement surface have positive correlation with pavement structure temperature. While specific heat, thermal conductivity emissivity, reflectance of pavement surface and wind speed have negative correlation with pavement structure temperature.

The influence of pavement surface parameters on near-surface temperature is quite different. The sensitivity order of pavement properties to near-surface temperature and pavement temperature in daytime high temperature period is reflectivity > slope A > emissivity > conductivity > density > specific heat. For sensitive parameters, for example, the accuracy of reflectance should be ensured to improve the accuracy of the model.

Based on the above research, some measures to improve the near-surface thermal environment can be obtained to alleviate the heat island effect of urban underlying surface and improve the thermal comfort of pedestrians. For example, research and development of new materials to properly improve the reflectivity of pavement materials and reduce solar radiation by planting trees and shading. However, comprehensive consideration should be given to the effects of changing pavement material properties.
and micro-environment meteorological conditions on thermal environment and surrounding building energy consumption and pavement life, so as to optimize the overall effect.

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References


