

Article

Numerical Analysis on the Optimization of Evaporative Cooling Performance for Permeable Pavements

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Abstract: The phenomenon of urban heat islands is mainly caused by the increase of artificially hardened surfaces in cities, and it can be alleviated by using permeable pavements to dissipate latent heat. There are many disagreements on the cooling effect of permeable pavements, and at present, it still needs more tests and modeling to prove this view. This paper proposes a 3-D transient model based on the heat transfer theory of porous media to accurately evaluate the cooling performance of permeable pavements. The influences of surface thermal parameters, storage depths, and spraying schemes on the cooling performance of permeable pavements are analyzed. The results show that compared with the peak temperature in the dry state, saturated permeable pavements can be significantly reduced. It is also found that the reflectivity of permeable pavements is positively correlated with the magnitude of temperature reduction and it has the most significant effect on the surface temperature among the discussed thermal parameters. A water storage layer with a thickness of 15 cm is recommended to balance economic costs and the cooling performance of permeable pavements. Based on the calculation results of the temperature reduction and cooling time, the optimal quantity of water spray is given innovatively. The proposed model can help improve the material components, structures, and maintenance methods of permeable pavements.

Keywords: urban heat island; permeable pavements; evaporative cooling; thermal parameters



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1. Introduction

Urban heat islands are a phenomenon in which urban green areas are covered by hardened surfaces with high specific heat capacities, such as buildings and roads, resulting in higher air and surface temperatures in the cities than in the suburbs [1,2]. Specifically, the rapid expansion of the urban scale has disrupted the balance of heat and water exchange between the natural soil interface and atmosphere, thus causing a series of urban thermal environmental problems [3,4]. Studies showed that artificially hardened urban surfaces account for about 40% of the urban surface [5]. Most of the materials used in the artificial ground are impermeable materials, which can easily absorb heat and then release it by long-wave radiation and convection heat exchange. These ways of heat transfer lead to the increase of the air temperature near the ground, thus aggravating the urban heat island effect [6,7].

Due to the indispensability of artificially hardened surfaces, it has become the focus of research to study the methods of cooling pavements to relieve the urban heat island effect. The moisture stored inside permeable pavements can take away part of the heat by evaporation, thus reducing the temperature of the road surface and the air temperature near the surface [8,9]. Permeable pavements are especially suitable in hot-humid regions, where the climatic characteristics are high temperature, abundant rainfall, and strong monsoon in summer, providing the prerequisite for evaporative cooling of permeable pavements [10–12]. Research on the evaporative cooling of permeable pavements mainly focuses on the development of materials, improvement of structures, and evaluation of

the outdoor thermal environment. The study approaches mainly include both numerical simulation and experiments. For example, based on the theory of Hydrothermal Transfer in Porous Media, Asaeda [13] proposed a 1-D hydrothermal transfer model for permeable pavements to predict the surface temperature and heat balance of permeable pavements with different porosity, while the 1-D model cannot completely reflect the true 3-D situation. Qin [14] developed a model to calculate the evaporation rate of pervious concrete pavements and found that the temperature of pervious pavements was lower than that of ordinary concrete pavements within 12 to 24 h after spraying. Again, these results are based on a simplified 1-D model. Wei [15] simulated the evaporative cooling process of permeable pavements using the surface water content as a variable, but the right quantity of water and spraying time could not be found. Kubilay [16] investigated the level of evaporative cooling reached after rain events and found that the evaporation of water from the surface of porous materials can effectively improve the urban thermal environment. However, the spraying scheme for hot and sunny days is not mentioned. In terms of testing, field tests [17–19] demonstrated that increasing the capillary suction or water content of the pavement materials could significantly reduce the temperature and prolong the cooling time. Yamagata [20] conducted artificial spraying tests on water-retaining pavements in Tokyo. The results showed that pavements' temperatures could be reduced by a maximum of 8 °C and 3 °C during the day and night, respectively, compared to those under the non-waterlogged condition. Takebayashi [21] showed that the maximum heat flow of the permeable asphalt and concrete in wet conditions could be reduced by 150 W/m² and 100 W/m², respectively. Numerical simulations can simultaneously consider environmental factors, and examine the effects of changes in permeable structural parameters on cooling, such as water content and porosity, etc. However, the current simplified 1-D model is not accurate enough. The effects of water transport and temperature change on cooling in permeable pavements are still unclear and therefore cannot effectively guide design and production.

To solve the above challenges, this paper proposed a 3-D and non-stationary model for permeable pavements based on the theory of Hydrothermal Transfer in Porous Media, and the accuracy of the model was verified by the measured data. On this basis, we furtherly compared the influence of various thermophysical parameters on the temperature field of permeable pavements and proposed the recommended spraying scheme.

2. Materials and Methods

2.1. Heat Transfer Theory

The energy exchange between the environment and permeable pavements is related to meteorological parameters including solar radiation, atmospheric inverse radiation, air temperature, wind speed, and rainfall. The regulation for permeable pavements mainly focuses on heat absorption from solar radiation. Part of the solar radiation is reflected into the atmosphere through the permeable surface and the rest is absorbed by pavements. The heat absorption induced by solar radiation can be divided into heat conduction G (W/m²), heat convection H (W/m²), net long-wave radiation L (W/m²), and evaporation E (W/m²), as shown in Figure 1, and the heat balance equation is shown in Equation (1).

$$I(1 - \rho) = G + L + H + E \quad (1)$$

The permeable pavement is a porous mixture made of a certain percentage of aggregate, water, cement, and sand. To simplify the analysis, the following assumptions are made:

1. The materials are assumed as homogeneous and isotropic, and thermal deformation is ignored.
2. Heat loss by viscosity dissipation and pressure changes is ignored.
3. Heat transfer in pores is neglected.
4. The heat exchange satisfies local equilibrium.

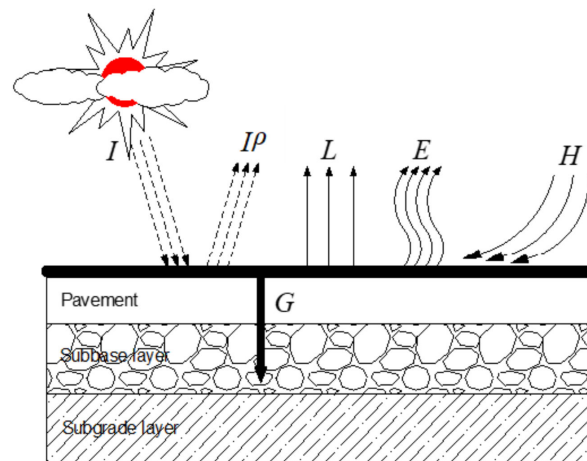


Figure 1. Energy component relationship of wet permeable pavements.

According to the local heat balance assumption, the controlling equation for heat transfer in porous media is

$$(\rho c)_m \frac{\partial T}{\partial t} + (\rho c_p)_f V \cdot \nabla T = \nabla \cdot (\lambda_m \nabla T) + \phi q_m \quad (2)$$

Further descriptions are as follows:

$$\lambda_m = (1 - \phi)\lambda_s + \phi\lambda_f \quad (3)$$

$$q_m = (1 - \phi)q_s + \phi q_f \quad (4)$$

$$(\rho c)_m = (1 - \phi)(\rho c)_s + \phi(\rho c_p)_f \quad (5)$$

The permeable surface continuously radiates energy outward by long-wave radiation when it absorbs solar radiation. The long-wave radiation of the surface is calculated using Equation (6)

$$L = \varepsilon \sigma (T_s^4 - T_{sky}^4) \quad (6)$$

where $\sigma(-)$ is the Boltzmann constant with a value of $5.67 \times 10^{-8} \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-4}$.

Convective heat exchange occurs between the surface of permeable pavements and the environment, according to Newton's law of cooling [22,23], heat convection H is found using Equation (7).

$$H = h_c (T_s - T_a) \quad (7)$$

where h_c is the convection heat transfer coefficient, $\text{W}/(\text{m}^2 \cdot \text{K})$, which can be estimated using Equation (8).

$$h_c = 5.6 + 4.0v \quad (8)$$

The heat due to the evaporation of water is evaluated by Equation (9).

$$E = ER \cdot L / 3.6 \quad (9)$$

2.2. Explanation of Modeling

2.2.1. Geometrical and Physical Parameters

The main source of water for evaporation is free, in the shallow part of permeable pavements. Water buried below the permeable surface layer cannot penetrate upward and therefore evaporation is rare [24,25]. To conservatively estimate the cooling performance of the surface layer, materials below the surface layer are assumed to be impermeable. A 3-D structure ($5 \text{ m} \times 5 \text{ m} \times 2 \text{ m}$) divided into four structural layers from top to bottom was developed, as shown in Figure 2. The typical parameters [26] of each layer are shown in

Table 1. Common permeable surface materials include permeable brick, asphalt, concrete, etc. Here, pervious concrete was selected as the typical surface material.

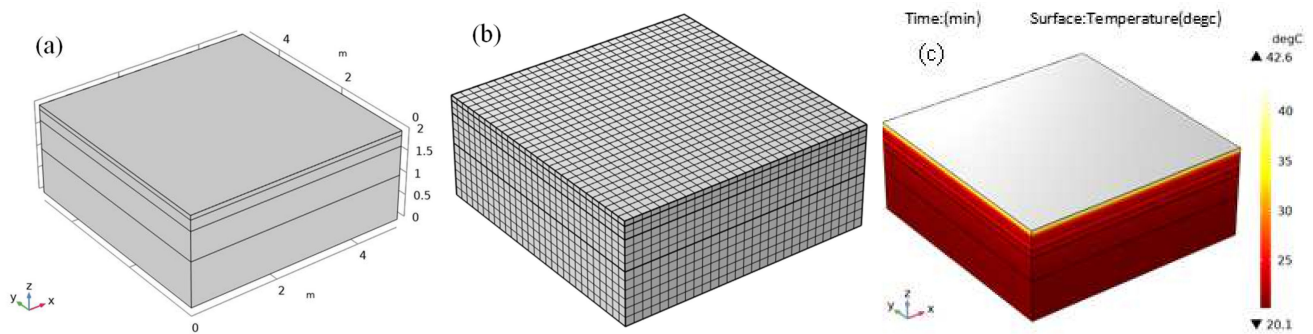


Figure 2. Modeling process. (a) Pavement layering, (b) Mesh generation, (c) Simulated results.

Table 1. Thickness and physical parameters of the permeable pavement.

Layer Name	Materials	Thickness (cm)	Density (kg/m ³)	Heat Capacity (J/(kg·K))	Thermal Conductivity (W/m·K)	Porosity (%)
Permeable surface layer	Permeable concrete	6	2000	880	0.68	20
Leveling layer	Cement mortar	15	2100	800	0.9	—
Base layer	Gravel	40	1400	900	0.55	—
Soil bedding	—	80	1700	840	1.78	—

2.2.2. Boundary Conditions

As shown in Figure 3, climatic parameters for typical hot-humid regions were entered into the model, located in Guangzhou, China. Based on our previous testing, the meteorological data were derived from Ref. [27]. The outdoor field experiment was carried out from 22 October 2017 to 25 October 2017. Local weather was monitored using an on-site portable weather station (from Spectrum Technologies, Inc.[®], Aurora, IL, USA). The perimeter and bottom surface were set as thermally insulated boundaries with an initial temperature setting of 20 °C. Ambient temperature, solar radiation, humidity, and wind speed were tested in Ref. [27] and imported into the model as the second type of thermal boundary conditions by interpolation functions, respectively (Figure 3).

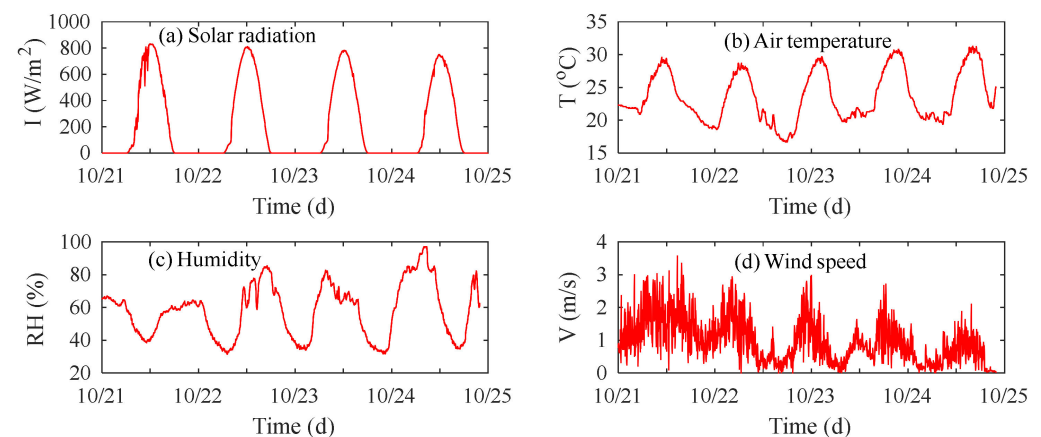


Figure 3. The weather condition at the experimental site.

2.2.3. Validation Model

To verify the accuracy of the numerical model, tested surface temperatures of permeable pavements in Ref. [27] were compared with the calculated results (Figure 4), with the spraying temperature set at 20 °C. As indicated in Ref. [27], the T-type thermocouple wires that have good stability and high sensitivity were used to measure the temperature of the pavement surface. The sensor was first attached to the permeable surface by thermal grease and the entire thermocouple was covered with aluminum foil. After fastening the sensors, the sensors were painted so that each paver surface had the same color to ensure that the pavement is evenly heated. The average value of the three measurement points was used to evaluate the surface temperature. It was found that in the dry state, the calculated results are consistent with the tested data, RMSE = 0.96 °C. There was a certain deviation in the fitting results in the wet state, which may be due to the influence of the temperature of the water leaching, leading to a large fluctuation of surface temperature. In addition, the fitting between the calculated and measured temperature of the wet permeable pavement at night fluctuated greatly, because the convective heat transfer on the surface at night is weak and condensation occurs, which leads to the simulated value being slightly lower than the measured value. Overall, the calculated results were consistent with the tested data, indicating that the model was accurate.

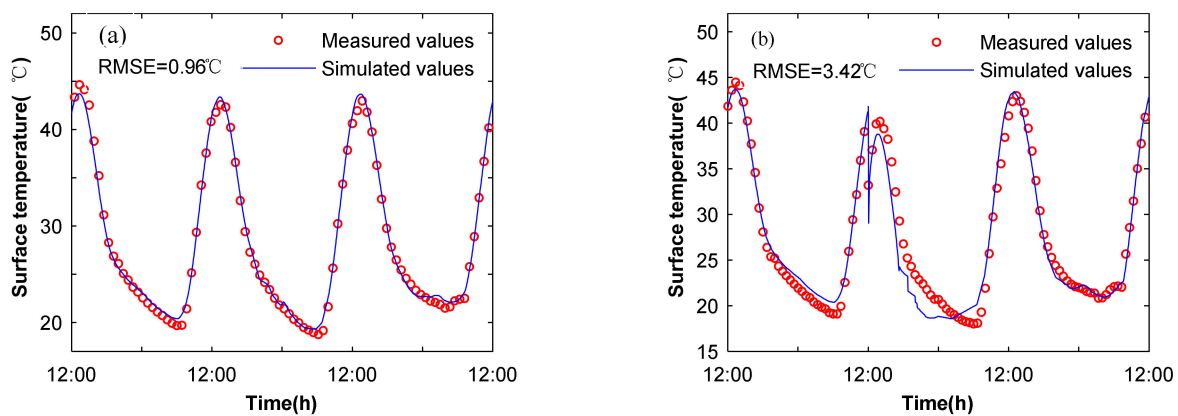


Figure 4. Simulated and measured values of the permeable surface temperature under dry and wet conditions. (a) Dry condition, (b) Wet condition.

3. Results

3.1. Effect of Thermal Material Parameters on Cooling

3.1.1. Reflectivity

Reflectance, the ratio of reflected radiation to incident one, directly reflects the absorption of solar radiation by the permeable surface layer. The reflectivity of the surface can be set by selecting "Diffuse surface module". The surfaces' temperatures were calculated based on presupposed reflectance. With the increased reflectivity of the permeable surface, the cooling effect would be more pronounced due to less heat absorption. Figure 5a shows that the maximum cooling in the wet state can be up to 6.8 °C. As the reflectivity increases, the road surface temperature decreases and the cooling time increases significantly, suggesting that increased reflectivity of permeable surfaces is beneficial for cooling. A linear relationship between reflectivity and temperature reduction is further shown in Figure 5b.

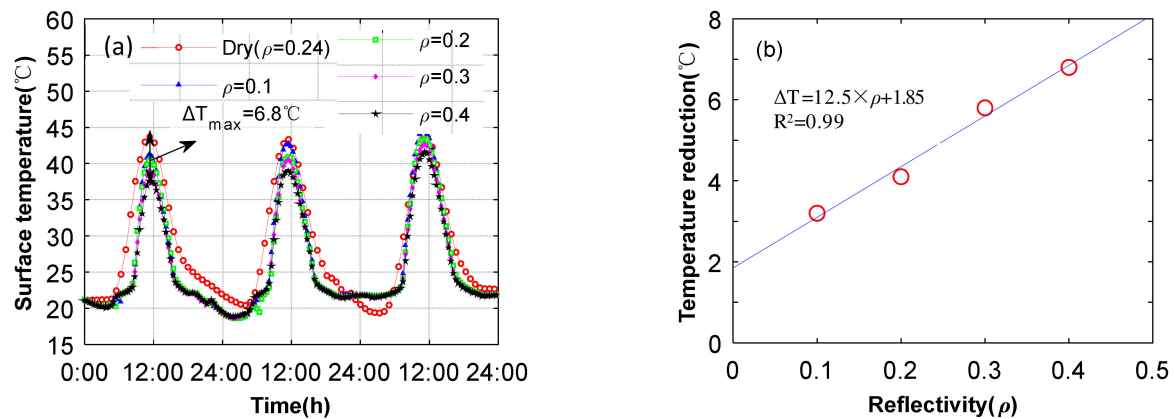


Figure 5. Cooling results of permeable surfaces with different reflectivities. (a) Diurnal surface temperature variation, (b) Cooling amplitude.

3.1.2. Emissivity

The emissivity of a permeable surface can reflect its ability to radiate thermal radiation. Similar to the method of calculating temperature by reflectance, the temperature reduction was calculated using different emissivities. Figure 6a shows the comparison of the results for wet and dry surfaces with different emissivities (0.6 to 0.9). Figure 6b indicates that the emissivity shows a positive correlation with temperature reduction. It is found that the temperature reduction of the permeable surface increases slightly with increasing emissivity. Moreover, the emissivity of a material is a stable parameter that is difficult to change.

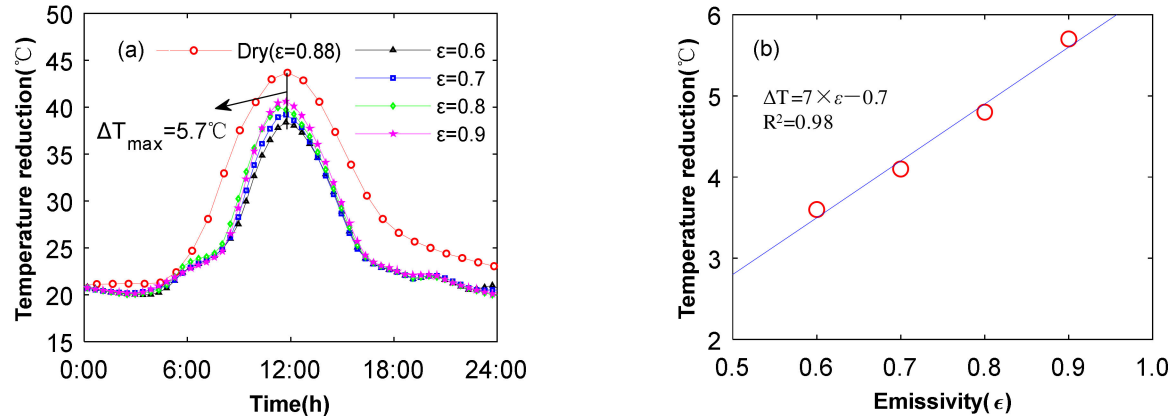


Figure 6. Surface temperature variation and cooling amplitude of permeable surfaces with different emissivities. (a) Diurnal surface temperature variation, (b) Cooling amplitude.

3.1.3. Specific Heat Capacity

Specific heat capacity, c , is a kind of thermal parameter that can reflect the heat absorption and dissipation of the object [28]. The surface temperatures of different specific heat capacities are relatively close in wet conditions and are all lower than the temperature of the dry one (Figure 7a). This indicates that the cooling is mainly contributed by the evaporation of water rather than the increasing heat capacity of the permeable surface. Figure 7b shows a negative linear correlation between the specific heat capacity and the maximum surface temperature. It is obvious that the specific heat capacity has less influence on the surface temperature.

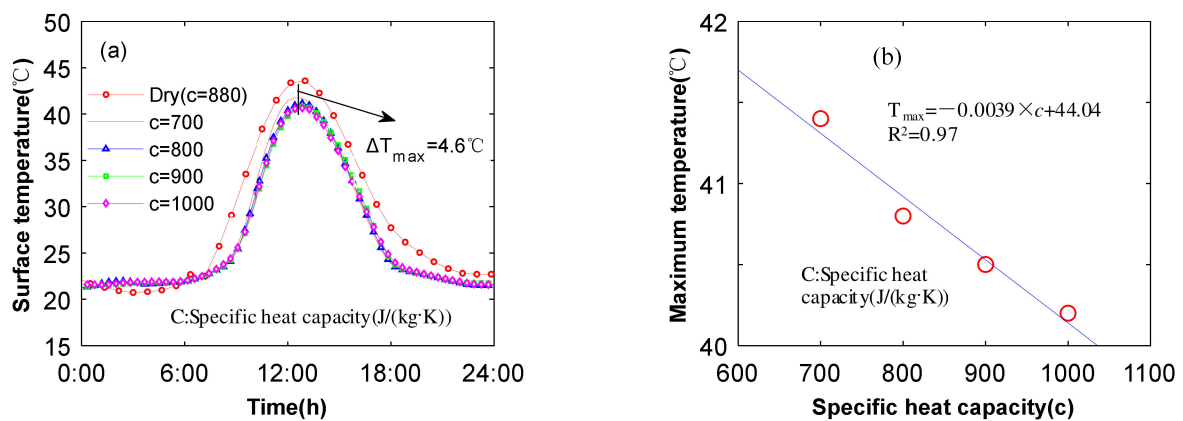


Figure 7. Temperatures of permeable surfaces with different specific heat capacities. (a) Diurnal surface temperature, (b) Peak temperature.

3.1.4. Thermal Conductivity

Thermal conductivity, k , is one of the thermophysical parameters of materials that affect the partition of solar absorption on the pavement surface and thus influences pavement surface temperature [29–31]. As shown in Figure 8a, thermal conductivity has a significant effect on the surface temperature during high-temperature hours (10:00 to 15:00), indicating that pavements with high thermal conductivity can keep cooling, because they conduct heat downward more efficiently. There is an approximately linear relationship between the thermal conductivity and the temperature reduction (Figure 8b), and this trend is more obvious in terms of low thermal conductivity.

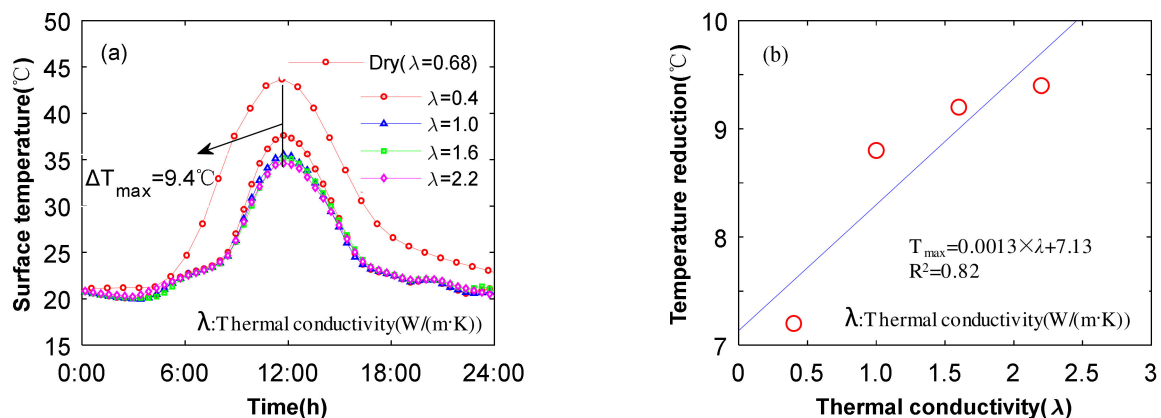


Figure 8. Cooling results of permeable surfaces with different thermal conductivity. (a) Diurnal surface temperature variation, (b) Cooling amplitude.

3.2. Effect of Depth of Water Storage Layer on Cooling

To evaluate the effect of permeable pavement structure on evaporative cooling, we assume that the moisture is only stored in the permeable surface layer. Figure 9 shows the influence of different aquifer thicknesses (5 cm, 15 cm, and 30 cm) on the temperature field inside the permeable pavement. It can be seen that the surface temperature of permeable pavement with aquifer thicknesses of 5 cm, 15 cm, and 30 cm are about 45 °C, 40 °C, and 33 °C, respectively. This trend seems to be reasonable because the dry saturated layer first appears on the pavement with thin aquifer thickness, and at this time, the evaporation of water mainly occurs inside the pavement, so the temperature of permeable pavement rises fastest. To further compare the temperature fields of permeable surfaces with different layer depths, we found that the temperatures below 15 cm thickness are almost the same, it may be that the water evaporation of permeable pavement at this depth is close to zero, and

the heat in this area is mainly transmitted by the heat conduction of permeable concrete skeleton.

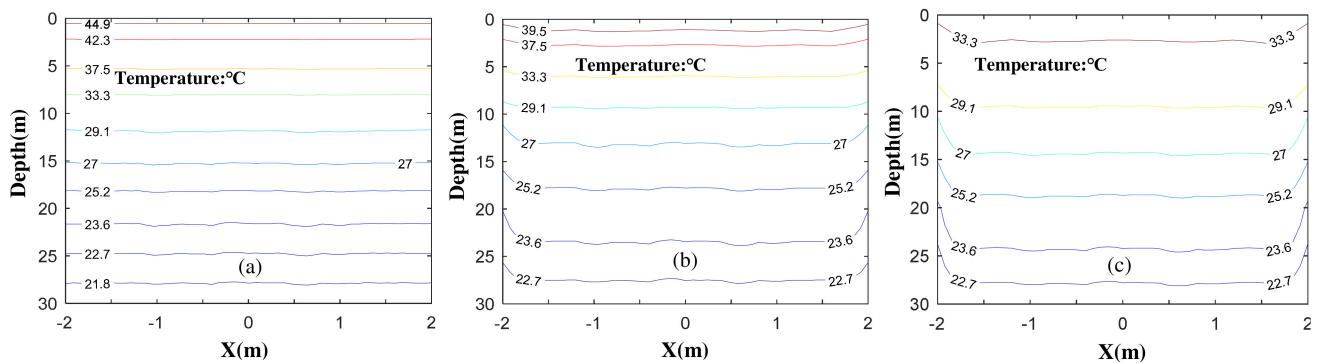


Figure 9. Temperature fields of permeable pavements with different storage layer depths at different depths. (a) 5 cm, (b) 15 cm, (c) 30 cm.

Similarly, the comparison of the concentration fields of permeable surfaces with 15 cm and 30 cm permeable layer thicknesses reveals that the change in water concentration below 15 cm is not significant as the thickness increases (Figure 10). This phenomenon is coincident with the findings of the study in Ref. [32].

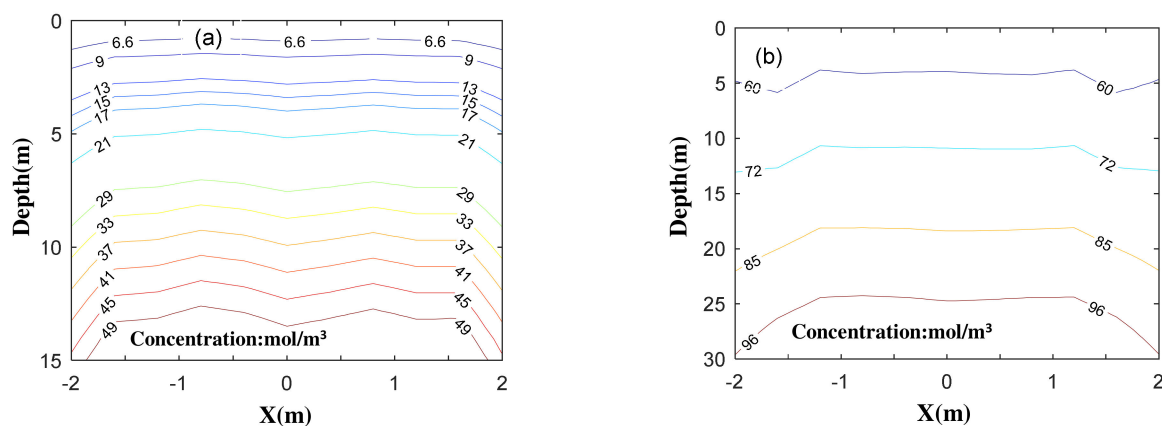


Figure 10. Concentration fields of permeable surfaces at different depths. (a) 15 cm, (b) 30 cm.

3.3. Pavement Spraying Scheme Selection

Three solutions with different time points of spraying were selected for comparison, and the evaporative cooling effect is evaluated in terms of cooling magnitude and duration. The permeable pavements with storage layer depths of 15 cm were set at a saturated state. It is found that the maximum decrease in surface temperatures is similar up to 8–12 °C. However, the cooling time under different sprinkling is different to some degree. When sprinkling at a low solar radiation intensity, that is, 10:00 am, it could effectively weaken the temperature peak later, and still could keep a surface cooling of 8 °C (Figure 11a). This is probably due to the loss of a large amount of water evaporation in the early stage and insufficient replenishment in the later stage. The difference is that a spray at 12:00 pm leads to a temperature plummet of 12 °C and can significantly weaken the subsequent maximum peak temperature (Figure 11b). As the solar radiation intensity goes down, the evaporation rate also decreases and eventually goes down to nearly zero during the night, the remaining water could also keep a high evaporation rate that maintains a low temperature up to 5–8 °C in the next morning. For spraying at 14:00 pm, although the surface can be effectively cooled, the solar radiation has turned weak; as a result, the evaporation time is limited, resulting in a short time to maintain the cooling (Figure 11c).

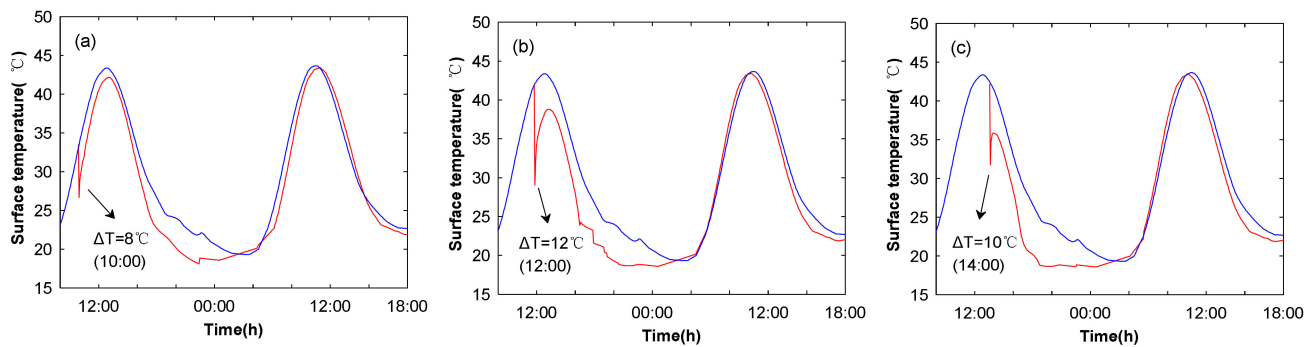


Figure 11. Variation of surface temperature during spraying at different times. (a) 10:00, (b) 12:00, (c) 14:00.

The effect of different single water quantities on the evaporative cooling process is shown in Figure 12, the spraying and compared time were set at 12:00 pm and 14:00 pm respectively. Both temperature reduction and cooling time were regarded as evaluation bases to find the suitable quantity of water. The calculation found that the two variables have obvious and close inflection points with the increase in water quantity. The inflection points of the two curves correspond to a water spray quantity of about 2.5 kg/m^2 . With increasing water quantity, the cooling is not significantly improved, which indicates that its potential is played. Accordingly, 2.5 kg/m^2 of water quantity basically meets the maximum evaporation capacity of permeable pavements.

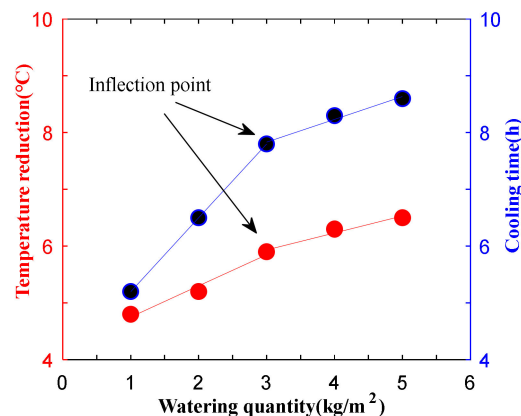


Figure 12. Optimum spray quantity.

4. Discussion

Although the meteorological environment is uncontrollable, the cooling performance of permeable pavements can be improved through reasonable structures and materials. In this paper, we compared the influence of various thermophysical parameters on the temperature field of permeable pavement in wet conditions, which has practical engineering significance for optimizing the design and research of this kind of pavement materials. Our results show that the most critical factor influencing the maximum surface temperature was albedo, followed by thermal conductivity and heat capacity, and lastly emissivity. If varying the minimum pavement surface temperature is the goal, albedo and emissivity can be regulated by staining surfaces with paint or adding color materials. Synnefa [33] compared several surfaces with different color paint and found that increasing the reflectivity of the surface influenced the process of solar energy transfer and effectively reduced the temperature of the surrounding environment.

However, regulating the pavement surface temperature via thermal conductivity is more effective than via volumetric heat capacity [34]. Chen's [35] study noted that the use of iron powder as an additive material increases the thermal conductivity of the surface layer, and the temperature drop by 1 to 3 °C compared to the conventional surface. There

are similar findings by Shi [36] et al. who investigated the parameter variation range of typical aggregates with possible thermal conductivity and heat capacity and found that thermal conductivity and heat capacity affect the maximum/minimum surface temperature in a similar manner. The change in thermal conductivity differs from a surface temperature up to 5.4 °C and that in heat capacity is 5.0 °C. This result is also confirmed by numerical calculations in this paper.

In addition, increasing the water storage performance of the surface layer is also an effective cooling method. Many candidate materials have been proposed as water-retentive fillers of pavement materials to retain more moisture, such as blast furnace slags [37] and biochar [38,39]. It was found that these fillers are indeed beneficial to the improvement of water retention performance, and the increase of pavement temperature is restrained by evaporative cooling. For structures design, the effect of reservoir thickness is the most significant. Our results found that 15 cm was the most suitable thickness that can balance economy and cooling performance. The improved surface structure is another direction in addition to reservoir thickness. Qin [40] invented permeable bricks that can intercept runoff for evaporation, which have obvious cooling performance under sufficient water. It is probably the most feasible way to prevent urban flooding and improve the thermal environment. The above suggestions can be used to help the design of permeable pavements and the next phase of research.

Active measures mainly refer to actions taken after the construction of the pavements such as water spraying. In Japan, the spraying of recycled wastewater on Permeable surfaces to mitigate the heat island effect has proven to be effective. Yamagata H [20] testified that the spraying can lower road temperatures by 8 °C during the day and 3 °C at night. The difficulty for the spraying technology depends on the selection of the time and quantity of water spraying. The results revealed that spraying water at 12:00 pm can achieve the optimum cooling performance as the solar radiation at this time is strong and lasts long enough for the permeable pavements to be sufficiently cooled. Based on the calculation results of temperature reduction and cooling time with water quantity, the recommended water spray quantity is creatively given using the inflection point of the two curves. This practical method for determining the amount of sprayed water can guide the maintenance of permeable pavements.

5. Conclusions and Prospects

In this paper, a 3-D multi-physics model with coupled fields is developed to investigate the effects of thermal properties and structures of permeable pavements on the evaporative cooling performance. Based on the calculation results, a new method to determine the optimal time and amount of water spraying was proposed.

The calculation results show that the peak temperature of the wetted pavements is significantly lower than dry ones, which greatly alleviates the thermal environment. The reflectivity and thermal conductivity of the surface have a significant effect on the cooling performance among the thermal property parameters of the surface layer. For structures design, the thickness of the water storage layer in pavement structure should be set to about 15 cm for the best benefit. In addition, based on the temperature reduction and duration of cooling, we found that spraying at 12:00 pm reaches the best cooling performance; that is, the relationships between the two and water quantity are not a simple linear increase, an inflection point is significant, which can be used as the optimal spraying volume.

The reflectivity, emissivity, specific heat capacity, and thermal conductivity of the permeable surfaces can be adjusted to improve cooling, but the benefits are different to some degree. Priority should be given to improving the reflectivity and thermal conductivity by adding blended materials. However, the properties of the surface layer, such as strength and durability, are changed in various ways due to the addition of materials. Such effects should be studied in the future. Methods to improve the surface structure also deserve attention. The proposed model can be used to comprehensively analyze the influence of thermal physical properties, water storage depths of pavement materials, and spraying schemes on

the evaporative cooling process. The results of the paper are helpful to the improvement of permeable pavement material composition, structures, and maintenance methods.

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Nomenclature

G	Thermal conduction (W/m^2)
H	Thermal convection (W/m^2)
L	Long wave radiation (W/m^2)
E	Evaporation (W/m^2)
I	Solar radiation (W/m^2)
T_s	Solid-phase temperature ($^{\circ}C$)
T_f	Liquid phase temperature ($^{\circ}C$)
T	Porous substrate temperature ($^{\circ}C$)
T_a	Air temperature ($^{\circ}C$)
RH	Ambient relative humidity (%)
ER	Surface evaporation rate ($kg/(m^2 \cdot h)$)
q_m	Apparent internal heat source heat production rate
q_s	Heat per unit volume of internal heat source of solids (W/m^3)
q_f	Heat per unit volume of internal heat source of fluids (W/m^3)
$(\rho c)_m$	Apparent heat capacity ($J/(kg \cdot K)$)
c_p	Specific heat capacity of fluids ($J/(kg \cdot K)$)
c	Specific heat capacity of solids ($J/(kg \cdot K)$)
λ_m	Apparent thermal conductivity ($W(m \cdot K)$)
λ_s	Thermal conductivity of solids ($W(m \cdot K)$)
λ_f	Thermal conductivity of fluids ($W(m \cdot K)$)
ϕ	Porous media porosity
ε	Emissivity
T_{sky}	Sky temperature ($^{\circ}C$)
ε_{sky}	Sky emission rate (-)
h_c	Convective heat transfer coefficient ($W/(m^2 \cdot K)$)
v	Wind speed (m/s)
ρ	Reflection

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