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Numerical analysis of temperature reduction effect of permeable pavements

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Abstract: Permeable pavements can effectively reduce the urban road surface temperatures. To study the cooling effect of holding water on the road surface under the comprehensive influence of the external water and heat environment, a numerical model established by a finite element analysis software and an indoor test were used to verify the temperature change behavior of the road surface under different heating temperatures and holding water conditions. The results show that the average error between the numerical model and indoor test is 3.5%, and the model reliability is high. Under the same conditions, the change in thickness of the permeable pavement surface and base course has a negligible effect on the temperature of the road surface. For every 100 J/(kg/°C) increase in the specific heat capacity of the upper surface course and lower surface course, the maximum daily road surface temperature can be reduced by approximately 2.1 °C and 0.4 °C, respectively. The road surface temperature shows a similar pattern when the thermal conductivity increases. Under dry conditions, the maximum daily road surface temperature can be reduced by approximately 3.4 °C and 4.3 °C for surface-permeable and fully permeable pavements, respectively. This study provides reference suggestions for optimizing the selection and design of urban

road pavement structures from the perspectives of permeable pavement design, material parameters, and structure type.

keyword: permeable pavement; finite element analysis; influencing factors; water holding status; road surface temperature; cooling effect

1 Introduction

With the rapid expansion of the urban scale and urban population, the phenomena of “urban rain island” and “heat island effect” have become increasingly serious (Sun et al. 2019; Zhou et al. 2012). The urban road permeable pavement is an important part of the “sponge city.” Compared with the traditional paved road, it has a large porosity and strong permeability, so that the rainwater within the city rapidly infiltrates the road surface, thus reducing the pressure of urban waterlogging (Niu et al. 2016; Roseen et al. 2009). It can store water while using water evaporation to take away heat from the road surface, therefore reducing the temperature of the road pavement and effectively alleviating the “heat island effect” of the city (Booth and Leavitt 1999; Haselbach et al. 2011; Ikechukwu 2015; Li et al. 2019). To date, scholars have conducted numerous studies on the drainage and cooling effects of permeable pavements. In terms of drainage action, Kuang et al. (Kuang et al. 2010) developed a permeability performance prediction model for permeable asphalt pavements to provide a reference for the analysis of the permeability capacity of permeable pavements. Li et al. (Hou et al. 2020; Palla et al. 2015) demonstrated the role of permeable pavements in relieving urban drainage pressure through indoor simulation tests. Wang (Hongshan 2017) established a rainwater infiltration model for permeable pavements and studied the influence of rainfall intensity on the rainwater infiltration of permeable pavements. Jiang et al. (Wei et al. 2013) established a water storage–infiltration model for permeable asphalt pavements based on meteorological and hydraulic theories to calculate and analyze their drainage effectiveness. Various studies have shown that permeable pavements can effectively infiltrate rainwater and reduce

43 surface runoff compared to conventional pavements, and the establishment of relevant infiltration models has
44 practical engineering significance. Regarding cooling studies, Chen et al. (Chen et al. 2017) showed that urbanization
45 has a significant impact on surface temperature and suggested that permeable pavements can be used to mitigate
46 urban thermal effects. Wang et al. (Liu et al. 2018; Wang et al. 2018) studied the effect of evaporative cooling of
47 permeable paving materials on the outdoor thermal environment. Li et al. (Li et al. 2013a; Li et al. 2016) found that
48 permeable pavements were effective in reducing the surface temperature in the wet state, but the opposite was true
49 in the dry, water-free state. Nemirovsky et al. (Li et al. 2014; Li et al. 2013b; Nemirovsky et al. 2013) found that
50 moisture near the surface in the permeable pavement construction layer has a large effect on cooling, and moisture
51 at deeper levels can be neglected. Nakayama et al. (Nakayama and Fujita 2010) used NICE-UBBREN to simulate
52 the cooling effect of urban permeable pavements in summer and showed that there is a strong relationship between
53 temperature decrease, surface evaporation, and pavement water capacity. Jiang (Fu 2011) used ANSYS to study the
54 cooling effect of a permeable pavement under the combined effect of heat conduction and heat convection, and the
55 results showed a positive linear relationship between its cooling effect and void fraction. Scholars mainly study the
56 cooling effect through outdoor measurements and mathematical models, and the analysis of the factors affecting the
57 cooling effect and its optimization is one of the active areas of research.

58 In summary, there have been numerous analyses on the various properties of permeable pavements, which have
59 laid the foundation for the research on drainage and temperature reduction of permeable pavement structures.
60 However, the existing studies have not addressed the influence of the permeable pavement structure thermal physical
61 parameters, pavement type, and water-holding state on road surface cooling. This study establishes the temperature
62 change calculation model of permeable pavement structures with the help of finite element analysis software,
63 calculates the temperature change of a permeable pavement structure under different conditions numerically,

compares the calculation results with the indoor test results, and verifies the reliability and accuracy of the parameter values of the numerical calculation model. It establishes a numerical calculation model of the road surface temperature of a real-size road pavement structure under actual environmental conditions and compares and analyzes the significant degree of influence of parameters such as thickness of the permeable pavement structure layer, specific heat capacity, and thermal conductivity of the material on the cooling effect of the road surface through the control variable method. It also compares the changes in road surface temperature of different types of pavement structures, further analyzes the differences in road surface temperature between non-permeable, surface-permeable, and fully permeable pavement structures under different dry and wet conditions, and analyzes the relationship between pavement type, water holding state, and road surface cooling effect.

2 Permeable pavement model

2.1 Finite element modeling

1) Introduction to finite element models

Because of the size limitation of the indoor test model, the actual road permeable pavement model could not be established. Thus, the finite element software was used to construct the numerical calculation model, and the reliability of the numerical model parameters was verified using the indoor test results. The numerical model set the side radiation coefficient to 0, the surface film condition was used to simulate the bottom surface and environmental boundary conditions, and the film coefficient was set to 200. To ensure the accuracy of the results, a model mesh size of $1\text{ cm} \times 1\text{ cm}$ was determined by comparison, and a four-node linear heat transfer (DC2D4) cell type was used for the heat transfer analysis. The permeable pavement structure model, from top to bottom, is as follows: surface structure of 15 cm, base course of 20 cm, and subgrade of 20 cm. The model width is 20 cm. The numerical model adopts upper thermal boundary conditions, and the indoor test is heated by an upper heating control device to maintain

consistency in all aspects and reduce the influence of differences in conditions on the results. A schematic of the model is shown in Figure 1.

(a) Indoor test plane 2-D model (b) Numerical calculation 2-D model

Figure 1 Schematic of indoor test and numerical calculation model

2) Model underlying assumptions

According to the basic characteristics of a permeable pavement, combined with the theoretical analysis and calculation requirements, the basic assumptions of the numerical calculation model were as follows:

- (1) Homogeneous and continuous medium for each layer of the permeable pavement structure;
- (2) The permeable pavement structure is isotropic, and its anisotropic characteristics are not considered;
- (3) The temperature and heat flow transfer of each structural layer of the permeable pavement is continuous, there is no thermal resistance in the contact between the layers, and the heat transfer interface effect between the layers is not considered.
- (4) The temperature at the bottom of the subgrade is constant, and the effect of geothermal action on the temperature of the subgrade pavement is not considered.
- (5) The model is fully insulated at each side boundary, and the heat dissipation effect of the model and heat exchange process with the outside world are not considered in the test.

101 (6) The permeable pavement surface is set to a state of no air flow, which is consistent with the wind-free
102 conditions of the indoor test.

103 3) Model parameter setting

104 The thermal conductivity of a permeable pavement material is less affected by external factors such as water
105 and air, and its comprehensive specific heat capacity should consider the action of air and water in addition to the
106 influence of asphalt and aggregate. The thermal conductivity of the pavement structure can be calculated according
107 to Williamson's formula²⁴. Pavement structure in the warming process, the volume and pressure are not changed,
108 can be regarded as equal volume and pressure specific heat capacity, dry and water-holding state of permeable
109 asphalt mixture and other pavement materials integrated specific heat capacity can be calculated according to for
110 the Eqs. 1 and 2.

$$111 \quad C_D = \frac{M_a}{M} \times C_a + \frac{M_s}{M} \times C_s + \frac{M_{air}}{M} \times C_{air} \quad (1)$$

$$112 \quad C_M = \frac{M_a}{M} \times C_a + \frac{M_s}{M} \times C_s + \frac{M_{air}}{M} \times C_{air} + \frac{M_w}{M} \times C_w \quad (2)$$

113 where C_D (J/(kg/°C)) is the integrated specific heat capacity of the structure in the dry state, C_M (J/(kg/°C)) is the
114 integrated specific heat capacity of the structure in the water-holding state, M (kg) is the structural mass, and the
115 subscripts a , s , air , and w are asphalt, aggregate, air, and water.

116 The relationship between the porosity V_{Void} and water holding capacity S_R of permeable pavement materials is
117 established through the available experimental data:

$$118 \quad S_R = 0.629 + 0.047 \times V_{Void} \quad (3)$$

119 where S_R (%) is the water retention rate of the specimen and V_{Void} (%) is the porosity of the specimen.

120 The numerical calculation model consists of three layers, and the model parameters include structural and
121 material parameters. The parameter values are listed in Table 1. For the calculation, the thermal conductivity,

122 structural layer density, and specific heat capacity were obtained from the established research results and Eqs. 1, 2,
 123 and 3.

124

125 **Table 1** Numerical model structure and parameters

Structural layer position	Thickness (cm)	Drying density (kg/m ³)	Water holding density (kg/m ³)	Dry specific heat capacity (J/(kg·°C))	Specific heat capacity holding water (J/(kg·°C))	Thermal conductivity (W/m·°C)
Permeable asphalt mixture surface course	15	2250	2287	865	990	0.7-1.1
graded crushed stone base course	20	2430	2495	850	1010	0.8-1.2
subgrade	20	1975	1997	850	995	0.8-1.5

126 2.2 Model reliability verification

127 The indoor test model for permeable pavement temperature change used a 20 cm in diameter, 80 cm in height,
 128 and 2 cm in thickness cylindrical glass test barrel. Model side with height scale, along the vertical direction every
 129 5cm set 1cm diameter small hole, for the drainage pipe and temperature sensor to leave the hole channel. Bury the
 130 temperature sensor as required. For the test, at the three interfaces, a PT100 RTD temperature sensor was used with
 131 display accuracy of 0.1 °C, and a 500 W round plate type cast aluminum electric heating plate was adopted for the
 132 upper surface temperature control heating. The indoor test model is shown in Figure 2.

(a) Permeable paving test bucket (b) Temperature sensor and drain pipe (c) Intelligent temperature control equipment (d) Model insulation wrap

133

134 **Figure 2** Indoor test model of permeable pavement

135 The numerical model used the same surface loading temperature and time as those of the indoor simulation test,
 136 with surface temperature loads of 40 °C, 50 °C, and 60 °C applied to the upper surface and a loading time of 12 h.
 137 The initial conditions inside the model were set to 29 °C. The drying and water holding states were controlled by
 138 changing the density, specific heat capacity, and thermal conductivity of each layer. The results of temperature
 139 variation at each depth location for the dry and water-holding state permeable pavement models were calculated
 140 under 12 h loading, and the inter-model error was calculated using Eq. 4.

$$141 \quad e = \frac{Abs(T_C - T_M)}{T_M} \times 100 \quad (4)$$

142 where T_C (°C) is the calculated value of the numerical model temperature, T_M (°C) is the measured indoor test
 143 temperature, e (%) is the computational error, and Abs is an absolute value function.

144 The experimental data were further analyzed, and the results of the comparison between the calculated values
 145 of the numerical model and the measured 45° contour plots of the indoor tests under surface heating conditions of
 146 40–60 °C are shown in Figure 3.

147 (a) 45° contour plot at 40 °C 148 (b) 45° contour plot at 50 °C 149 (c) 45° contour plot at 60 °C

Figure 3 45° contour plot of measured and calculated values at 40–60 °C

150 From the results of the 45° contour map in Figure 3, it can be observed that the obtained points in the coordinate
 151 system are basically near the 45° contour, there are no obvious data anomalies, and the resultant errors are well
 152 correlated with the depth of the model location. The average calculation errors of the 5, 10, and 15 cm surface depth

153 locations for each loading condition were calculated to be 7.18%, 4.69%, and 4.04%, respectively. At the 40 °C,
154 50 °C, and 60 °C loading conditions, 39% and 61%, 29% and 71%, and 28% and 72% of the total data volume were
155 accounted for by the upper left and lower right data of the contours, respectively. From the 45° contour map and the
156 average error calculation of the depth position of the surface layer, it can be observed that the points where the model
157 calculated value is higher than the measured value are mainly distributed in the higher temperature interval; that is,
158 the model calculated value in the upper depth region is slightly higher than the measured value. This is due to the
159 fact that the thermal boundary conditions of the upper surface of the calculated model do not consider heat loss during
160 the heating process, which produces differences with the actual indoor tests. With increasing depth, the effect of heat
161 loss gradually decreases, and the calculated error between the calculated and measured values gradually decreases.

162 In summary, the error interval between the calculated value of the numerical model and the measured value of
163 the indoor test was 0.1%–15%, with an average error of 3.5%, and the Pearson correlation coefficient was higher
164 than 0.8 under all conditions, which was a strong correlation result. The finite element model results correlate well
165 with the measured values of indoor tests, and the calculation results of the temperature change of the permeable
166 pavement in dry and water-holding states have high accuracy and good reproducibility of the temperature change
167 process, which provides a basis for the parameter setting of urban road paving models.

168 2.3 Modeling of permeable pavement for urban roads

169 To study the factors influencing the cooling of the pavement of a permeable pavement structure of actual urban
170 roads and the difference in road surface temperature changes in different types of urban road pavements under
171 different water holding conditions, and to provide a reference for the design and optimization of permeable pavement
172 structures from the perspective of the road surface cooling behavior, three models of an urban road permeable
173 pavement structure with a width of 700 cm (standard width of two lanes) under actual solar radiation conditions were

174 established, which are non-permeable, surface-permeable, and fully permeable pavement structures. The numerical
 175 calculation of the road surface temperature change process and the solar radiation intensity change curve is presented
 176 in Figure 4.

177
 178 **Figure 4** Daily variation curve of solar radiation intensity

179 The specifications of the material and thickness of the three road paving structures, A, B, and C, are listed in
 180 Table 2.

181 **Table 2** Road paving type specifications

Pavement type	Parameters	Model layers		
		Upper surface course	Lower surface course	Base course
Type A Non-permeable pavement	Material Type	AC-13	AC-13	cement stabilized macadam
	Thickness (cm)	10	20	20
Type B Surface-permeable pavement	Material Type	OGFC-13	AC-13	cement stabilized macadam
	Thickness (cm)	10	20	20
Type C Fully permeable pavement	Material Type	OGFC-13	ATPB	graded broken stone
	Thickness (cm)	10	20	20

182 According to the research results (Hui et al. 2012; Williamson 1972; Yan-xia et al. 2015), the OGFC-13 type
 183 surface-permeable asphalt mixture porosity was set to 20%, with water holding rate of 1.58% and dry and water
 184 holding state integrated specific heat capacity of 865 J/(kg/°C) and 995 J/(kg/°C). The AC-13 type surface layer
 185 porosity was set to 5.5%, with water holding rate of 0.887% and dry and water holding state integrated specific heat

capacity of 824 J/(kg/°C) and 853 J/(kg/°C). The ATPB type surface layer porosity was set to 22%, with water holding rate of 1.663% and dry and water holding state integrated specific heat capacity of 860 J/(kg/°C) and 915 J/(kg/°C). The porosity of the base course cement-stabilized gravel mix was set to 5.1%, with water-holding rate of 0.868% and combined specific heat capacity of the dry and water-holding states of 811 J/(kg/°C) and 840 J/(kg/°C). The water-holding rate of the base graded gravel mix was 4.27% using the indoor test results, and the combined specific heat capacity of the dry and water-holding states was 850 J/(kg/°C) and 1010 J/(kg/°C), respectively. The variation in the water holding rate had a small effect on the thermal conductivity, and the results were all calculated by Williamson's formula and then taken as a constant value.

3 Analysis of the factors influencing the cooling of a permeable pavement

3.1 Analysis of the influence of structural layer thickness parameters

To analyze the influence of different thickness parameters of a permeable pavement on the surface temperature during the warming process, the thickness parameters of the upper surface course, lower surface course, and base course were changed, and the other parameters of each layer were set to constant values. This allowed comparing the changes in the road surface temperatures of permeable pavements with different thicknesses under the same loading conditions.

(1) Effect of thickness of the upper surface course

The thickness of the upper surface course of OGFC was set to 4, 6, 8, 10, and 12 cm, the lower surface course was 20 cm ATPB material, the base course was 30 cm graded gravel material, and the thickness of the subgrade was 100 cm.

(2) Effect of thickness of the lower surface course

The thickness of the upper surface course of OGFC was set to 5 cm, the thickness of the lower surface course

207 of ATPB was set to 10, 15, 20, 25, and 30 cm, and the thickness of the base course and subgrade remained unchanged.

208 (3) Effect of thickness of the base course

209 The thickness of the upper surface course of OGFC was set to 5 cm, the thickness of the lower surface course
210 of ATPB was set to 20 cm, the thickness of the base course was set to 20, 25, 30, 35, and 40 cm, and the subgrade
211 remained unchanged.

212 Under the above parameters, the numerical calculation of road surface temperature under 12 h loading conditions
213 was carried out, and the curves of road surface temperature variation with loading time were plotted for different
214 layer thickness parameters of the permeable pavement, as shown in Figure 5.

217
218
219 **Figure 5** Effect of thickness on the temperature of the permeable pavement surface

220 As can be observed from Figure 5, the trend of change in road surface temperature of the permeable pavement

under each change in layer thickness is basically the same, and the road surface temperature change curves obtained by changing the thickness parameters of the upper surface course, lower surface course, and base course overlap. The calculation results of road surface temperature under different surface course and base course thicknesses are basically the same. It can be observed that under the same environmental conditions, the structural layer thickness parameters do not have a significant effect on the cooling effect of the permeable pavement road surface. From the perspective of the design of permeable pavements, the thickness of the permeable pavement structure should be determined according to the actual requirements of road bearing capacity and permeability performance.

3.2 Analysis of the effect of specific heat capacity parameters

To analyze the influence of the specific heat capacity parameters of different layers of a permeable pavement on the surface temperature during the warming process, the values of specific heat capacity parameters of the upper surface course, lower surface course, and base course of the permeable pavement were changed, and the change in temperature of the road surface was compared under the same other conditions. The parameters of the permeable paving model used were 5 cm OGFC-13 mix for the upper surface course, 20 cm ATPB mix for the lower surface course, 40 cm graded gravel for the base course, and a 100 cm subgrade was set.

(1) Effect of specific heat capacity parameter of upper surface course

The specific heat capacity of the upper surface course of OGFC was set to 800, 900, 1000, 1100, and 1200 J/(kg/°C), and the other parameters remained unchanged.

(2) Influence of specific heat capacity parameter of the lower surface course

The specific heat capacity of the lower surface course of ATPB was set to 800, 900, 1000, 1100, and 1200 J/(kg/°C), and the other parameters remained unchanged.

(3) Influence of specific heat capacity parameter of the base course

The specific heat capacity of the graded gravel base was set to 800, 900, 1000, 1100, and 1200 J/(kg/°C), and the other parameters remained unchanged.

Under the above parameters, the numerical calculation of the road surface temperature under actual loading conditions for 12 h was carried out, and the change curve of the road surface temperature with loading time was plotted under the change in specific heat capacity parameters of the different layers of the permeable pavement. The results are shown in Figure 6.

Figure 6 Effect of specific heat capacity on the temperature of permeable pavement surface

From Figure 6, it can be observed that the change in specific heat capacity of the upper surface course has a more significant effect on the temperature change of the permeable pavement surface, with a temperature difference

of 8.5 °C at the highest point and 6.9 °C after the loading is completed. For every 100 J/(kg/°C) increase in the specific heat capacity of the upper surface course material, the maximum daily temperature of the road surface can be reduced by approximately 2.1 °C. The change in the specific heat capacity of the lower surface course material has a low impact on the road surface temperature, with a maximum temperature difference of 1.4 °C. For every 100 J/(kg/°C) increase in the specific heat capacity of the material, the temperature decreases by approximately 0.4 °C, which is significantly lower than the upper surface course results. For the base course, the change in specific heat capacity at this location has almost no effect on the road surface temperature. As can be observed from Figure 8(d), the maximum daily road surface temperature decreases with an increase in the specific heat capacity of the upper surface course and the lower surface course, the trend gradually becomes slower, and the influence on the road surface temperature gradually decreases. In summary, the change in the specific heat capacity of the upper surface course of a permeable pavement has a more significant effect on the temperature of the permeable pavement surface, and the degree of influence gradually decreases with increasing depth.

3.3 Analysis of the influence of thermal conductivity parameters

Referring to the range of thermal conductivity values in the established research results, the values of thermal conductivity parameters of the upper surface course, lower surface course, and base course of the permeable pavement were changed to compare the change in temperature of the road surface. The model was a 5 cm OGFC mix for the upper surface course, 20 cm ATPB mix for the lower surface course, 40 cm graded gravel for the base course, and a 100 cm subgrade was set.

(1) Influence of thermal conductivity parameters of the upper surface course

The thermal conductivity of the upper surface course of OGFC was set to 0.6, 0.7, 0.8, 0.9, 1.0 W/(m/°C), and

the other parameters remained unchanged.

(2) Influence of thermal conductivity parameters of the lower surface course

The thermal conductivity of the lower surface course of ATPB was set to 0.6, 0.7, 0.8, 0.9, and 1.0 W/(m/°C), and the other parameters remained unchanged.

(3) Influence of thermal conductivity parameters of the base course

The thermal conductivity of the graded gravel base was set to 0.9, 1.0, 1.1, 1.2, and 1.3 W/(m/°C), and the other parameters remained unchanged.

Under the above parameters, the calculation of the road surface temperature values under 12 h loading conditions was carried out. The curves of road surface temperature with loading time for the different layers of the permeable pavement by changing the thermal conductivity parameters were plotted, and the results are shown in Figure 7.

(a) Upper surface course

(b) Lower surface course

(c) Base course (d) Maximum surface temperature of the road on a day
Figure 7 Effect of thermal conductivity on the temperature of permeable pavement surface

As can be observed from Figure 7, the change in thermal conductivity of the upper surface course has a significant effect on the temperature change of the permeable pavement surface, with a temperature difference of 3.9 °C at the peak temperature and 3.5 °C after the completion of the 12 h loading process. For every 0.1 W/(m°C) increase in the thermal conductivity of the material, the maximum daily temperature of the road surface is reduced by approximately 0.9 °C. The degree of influence of the change in thermal conductivity within the lower surface course structure on the road surface temperature is relatively low, whereas the change in thermal conductivity of the subgrade has almost no influence on the road surface temperature. It can be observed that the effect of the change in thermal conductivity on the cooling effect of the permeable pavement surface decreases gradually with an increase in the depth of the structure. As can be found from Figure 9(d), the maximum daily road surface temperature decreases with an increase in the thermal conductivity of the upper surface course and the lower surface course, the trend gradually becomes slower, and the influence on the road surface temperature gradually decreases.

From the perspective of permeable pavement material parameters, an upper layer with a larger specific heat capacity or thermal conductivity of the material, or the use of modified materials and additives to change the comprehensive specific heat capacity or thermal conductivity of the material, can result in better cooling effect on

305 the road surface. The effect of the thermal parameters of the materials of the following layer, the grassroots level, and
306 other deeper layers on the road surface cooling effect is low. Therefore, to achieve an optimal cooling effect, priority
307 should be given to modification of the material of the permeable pavement upper layer.

308 4 Analysis of cooling effect of the permeable pavement surface

309 Urban road pavement because of high heat absorption rate, low specific heat capacity, a large amount of heat
310 absorption in the short heating time, the surface temperature rises rapidly, and as a heat source of near surface
311 continuous heating, resulting in the road surface near the temperature rise, intensifying the urban "heat island effect".
312 To analyze the differences in the road surface temperature changes of different urban road pavements, the non-
313 permeable, surface-permeable, and fully permeable pavement types in the dry state were recorded as Ad, Bd, Cd, and
314 those in the water-holding state were recorded as Aw, Bw, Cw. The road surface temperature changes during 12 h in
315 the dry and water-holding states were calculated to analyze the effects of road pavement types and dry and wet states
316 on the road surface temperature.

317 4.1 Comparison of road surface temperature in dry and water-holding condition

318 To analyze the difference in surface temperature during the warming process of the three pavement structures
319 under dry and water-holding conditions, and to compare the changes in the temperature data of different pavement
320 types, the change curve of surface temperature with loading time is drawn, and the comparison results are presented
321 in Figure 8.

(a) Dry condition (b) Water-holding condition
Figure 8 Comparison of road surface temperatures in dry and water-holding conditions

As can be observed from Figure 8(a), the temperature of the non-permeable road surface during the warming process in the dry state is significantly higher than that of the permeable pavement, and the maximum daily temperature of the road surface of type A is 3.4 °C and 4.3 °C higher than those of types B and C, respectively, and 2.6 °C and 3.9 °C higher than those of types B and C at the end of warming. The maximum daily road surface temperature of the surface-permeable pavement is approximately 1.3 °C higher than that of a fully permeable structure. Under dry conditions, the difference in road surface temperature is mainly reflected in the non-permeable and permeable pavements, and the trend of changes in road surface temperature with time is the same for the three pavement structures.

As can be observed from Figure 8(b), during the warming process of the non-permeable road pavement in the holding water state, the road surface temperature is significantly higher than that of permeable pavement. The maximum daily road surface temperatures of type A are 5.8 °C and 8.1 °C higher than those of types B and C, respectively, and 5.7 °C and 7.8 °C higher than those of types B and C at the end of warming. The maximum daily road surface temperature of the surface-permeable pavement is approximately 2 °C higher than that of a fully permeable structure, and its temperature can be approximately 1.8 °C higher at the end of the warming and loading

process. The three types of permeable pavements produce a difference in road surface temperature between 0–1.9 °C owing to the different water holding ranges, and the difference in road surface temperature between non-permeable and permeable pavements increases slowly under different warming time domains, reaching a temperature peak when the temperature difference reaches a maximum value, and then decreases as the road surface temperature decreases.

4.2 Analysis of the effect of water-holding effect of permeable pavement on road surface temperature

To analyze the effect of the water-holding effect on the temperature of a permeable pavement road surface, the curves of the change in road surface temperature with loading time in the dry and water-holding states of the B and C permeable pavement structures were plotted, and the results are presented in Figure 9.

(c) Comparison of temperature difference between wet and dry road surfaces by pavement type

Figure 9 Comparison of road surface temperature of permeable pavement in dry and water-holding condition

From Figure 9, it can be observed that the trend of temperature change of permeable pavement types B and C

under dry and water-holding conditions is basically the same. The class B surface-permeable pavement has a maximum daily road surface temperature difference of 3.5 °C between the dry and wet conditions and 3.4 °C after 12 h. The class C fully permeable pavement has a maximum daily road surface temperature difference of 4.9 °C between the dry and wet conditions and 3.9 °C after loading is completed. Because of the different levels of permeable layers, the effect of water retention on the cooling effect of each type of permeable pavement is slightly different, and the effect of water retention of the surface layer permeable pavement on the road surface cooling is relatively weaker than that of the fully permeable type of pavement. From the perspective of permeable pavement structure type, a fully permeable pavement structure has an excellent road surface cooling effect.

5 Conclusion

This paper provides reference suggestions for the optimization of permeable pavement surface cooling from three perspectives: design, material parameters, and structure type, with the following main conclusions:

(1) Under the same environmental conditions, it is difficult to influence the road surface temperature of a permeable pavement by changing the thickness of each structural layer, and the structural layer thickness parameter does not have a significant effect on the cooling effect of the road surface.

(2) The change in the specific heat capacity of the upper surface course of a permeable pavement has a more significant effect on the temperature of the permeable pavement surface, and the degree of influence gradually decreases with increasing depth. For every 100 J /(kg/°C) increase in specific heat capacity of the upper and lower surface courses, the maximum daily road surface temperature can be reduced by approximately 2.1 °C and 0.4 °C, respectively, under the same warming environment.

(3) The effect of change in thermal conductivity on the cooling effect of a permeable pavement surface gradually decreases with an increase in the depth of the structure, and the change in thermal conductivity of the upper

surface course of the structure near the surface of the road has a relatively high degree of influence on the cooling effect of the road surface. For every 0.1 W/(m/°C) increase in thermal conductivity of the upper and lower layers, the maximum daily road surface temperature can be reduced by approximately 0.9 °C and 0.2 °C, respectively.

(4) Under the same warming environment, the maximum daily road surface temperature of the surface-permeable and fully permeable pavements in the dry state can be reduced by approximately 3.4 °C and 4.3 °C compared to non-permeable pavement, and can be reduced by approximately 5.8 °C and 8.1 °C, respectively, in the water-holding state. The maximum daily road surface temperatures in the dry and water-holding states of the fully permeable pavement can be reduced by approximately 1.3 °C and 1.8 °C, respectively, compared with those of the surface-permeable pavement, and the cooling effect is better than that of the surface-permeable pavement.

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461 The authors declare that they have no competing interests.

Figures

(a) Indoor test plane 2-D model (b) Numerical calculation 2-D model

Figure 1

Schematic of indoor test and numerical calculation model

(a) Permeable paving test bucket (b) Temperature sensor and drain pipe (c) Intelligent temperature control equipment (d) Model insulation wrap

Figure 2

Indoor test model of permeable pavement

Figure 3

45° contour plot of measured and calculated values at 40–60 °C

Figure 4

Daily variation curve of solar radiation intensity

(a) Upper surface course

(b) Lower surface course

(c) Base course

Figure 5

Effect of thickness on the temperature of the permeable pavement surface

Figure 6

Effect of specific heat capacity on the temperature of permeable pavement surface

(a) Upper surface course

(b) Lower surface course

(c) Base course

(d) Maximum surface temperature of the road on a day

Figure 7

Effect of thermal conductivity on the temperature of permeable pavement surface

(a) Dry condition

(b) Water-holding condition

Figure 8

Comparison of road surface temperatures in dry and water-holding conditions

(a) Surface-permeable type structure

(b) Fully permeable structure

(c) Comparison of temperature difference between wet and dry road surfaces by pavement type

Figure 9

Comparison of road surface temperature of permeable pavement in dry and water-holding condition