Characterizing Thermal Impacts of Pavement Materials on Urban Heat Island (UHI) Effect

Hao Wu¹, ², Zhuo Liu³, Yan Yang⁴, and Shu Bai⁵

¹Associate Professor, School of Civil Engineering, Central South University, 22 South Shaoshan Rd., Changsha, Hunan, 410075, P.R. China. E-mail: haoutk@csu.edu.cn.
²National Engineering Laboratory for High Speed Railway Construction, Central South University, 22 South Shaoshan Rd., Changsha, Hunan, 410075, P.R. China.
³Graduate student, School of Civil Engineering, Central South University, 22 South Shaoshan Rd., Changsha, Hunan, 410075, P.R. China. E-mail: 907820785@qq.com.
⁴Hunan Architectural Advanced Technical School, 11 Guduishan Lane, Nanhu Rd., Changsha, Hunan, 410015, P.R. China. E-mail: 19953399@qq.com.
⁵Hunan Provincial Communications Planning Survey & Design Institute, Changsha, Hunan, 410075, P.R. China. E-mail: cby_shu@126.com

ABSTRACT: Pavements are one of the major contributors to the urban heat island (UHI) effect of cities because they cover a considerably large fraction of urban ground surfaces. Permeable pavements are considered an effective solution for mitigating the heat island effect in hot climates. In this study, the effect of pavement types on mitigating the UHI was investigated through a series of laboratory simulation experiments. Three commonly used pavement materials, asphalt concrete (AC), traditional Portland cement concrete (PCC), and Portland cement porous concrete (PCPC), were considered for the study. The thermal performances of those materials under simulated conditions were examined with specially designed testing methods. The testing results showed that under the same thermal radiation conditions, the surface temperature of PCPC was equivalent to that of PCC, whereas the AC showed much higher surface temperature. This indicates that AC pavements usually absorb more heats than PCC and PCPC pavements under solar radiations. Compared to the PCC, the AC and PCPC usually reflected less heat to the surrounding environments due to their relatively lower albedo values, which could mitigate the thermal discomfort for the nearby human and buildings to some extent. In addition, the PCC could store more thermal energy in day time and release them back to the atmosphere at night due to its relatively high density, thermal conductance and specific heat capacity. This indicates that PCC could produce negatively effects on the UHI at night.

INTRODUCTION

Increased awareness of the urban heat island (UHI) effect has raised major attentions on the dwelling comfort of human in urban areas. By increasing daytime temperature of both pavement and near-surface air and reducing nighttime cooling, the UHI effect could harm human health by contributing to general discomfort, respiratory difficulties and even heat related mortality[1-4].
As well known, pavements are recognized as one of the major contributors for the UHI effect, because they cover a considerably large fraction of urban ground surfaces [5-7]. Pavement materials, such as cement concrete and asphalt concrete, have relatively higher solar energy absorption and tend to trap a relatively higher incoming solar radiation. They also possess a higher heat storage capacity that allows them to retain heat in daytime and then slowly release the heat back into the atmosphere at night. Meanwhile, the UHI effect could also jeopardize the performances and shorten the lives of pavements by bring them long-term high temperature service conditions. For asphalt concrete (AC) pavements, continuous high temperatures in summer can significantly increase the risk of rutting and aging distresses; while for Portland cement concrete (PCC) pavements, high temperature and temperature gradient can significantly increase the probability of thermal cracking.

The heat island effect might not be a black-and-white issue with respect to pavement type (asphalt vs. cement concrete), as currently argued in the pavement industry; rather, it may be an impermeable and permeable issue [8,9]. In recent years, the applications of alternate pavement designs have become more and more common in attempting to mitigate environmental impacts of urbanization [10,11]. Specifically, use of porous pavements, such as Portland cement porous concrete (PCPC), has gained popularity in pavement engineering due to the benefits of reducing storm runoffs and improving friction properties, as well as mitigating the UHI effect [12-14].

OBJECTIVE AND SCOPE

The main objective of this study was to evaluate the effect of pavement materials on mitigating the UHI effect. Three types of commonly used pavement materials, PCC, AC and PCPC, were considered in the study. The thermal properties of those materials and their thermal performances under simulated conditions were examined with standardized or specially designed testing methods. The effect of PCPC pavement on mitigating UHI effect can be evaluated by comparing to PCC and AC pavements.

EXPERIMENTAL STUDY

Specimen preparation

Three types of pavement materials, PCC, PCPC, and AC, which are commonly used in municipal pavement engineering are considered for the experiments. The PCC and PCPC samples are all molded in foam boxes with the dimensions of 300 mm long, 180 mm wide, and 140 mm high. Before adding fresh mixtures into the box, two temperature transducers were pre-embedded in the box for the measurement of temperatures during the test. One of the transducers was placed 30 mm below the surface, the other one was placed 30 mm above the bottom. The effective porosity of the PCPC specimen was 25.8%. The AC specimens were composed of three layers of asphalt concrete slabs with 30 mm, 70mm and 30 mm in height, respectively. Each
layer of the specimen was coated with rubber modified asphalt with 5 mm in thickness. The specimens used for the study are shown in Fig. 1.

![Specimens](image)

**Figure 1. Testing specimens for the study.**

**Albedo test**

Albedo, also called as reflection coefficient, is the fraction of solar energy reflected from the reflecting surface, such as pavements, back into space. It can be used to estimate the ability of pavements to absorb the solar radiation. Generally, a pavement with higher albedo absorbs less solar radiation, and reflects more back to the surroundings. Albedo is related to the roughness and color of the pavement surface, and a pavement with rougher and darker surface usually features lower albedo.

A laboratory test in accordance with ASTM E1918-06 “Standard Test Method for Measuring Solar Reflectance of Horizontal and Low-Sloped Surfaces in the Field” was specially designed to measure the albedos of the pavement materials in this study [15]. In the test, a calibrated infrared lamp was placed above each specimen to provide uniform thermal radiations on the specimen. A solar power meter was used to measure the incident light intensity and reflection light intensity of the specimen under the thermal source. The albedo of the specimen can be calculated with following equation:

\[ \alpha = \frac{P_1}{P_2} \]  

Eq. (1)

where, \( \alpha \) is the albedo of the specimen; \( P_1 \) is the incident light intensity; \( P_2 \) is the reflective light intensity.

Due to the measurement inaccuracy caused by artificial errors, the tests were performed at various heights from the specimen’s surface, and the albedo of the specimen was determined as the average value.

**Thermal radiation simulation test**

The simulation test was carried out in an enclosed room to ensure the testing condition would not affected by the environment. An infrared lamp was placed 500 mm above each specimen as the thermal source simulating solar radiation. The temperatures in the surface and bottom of the specimen were measured with the temperature transducers embedded in the specimen. The near surface air temperature were measured with the temperature transducers placed 35 mm above the surface of the specimen. A data acquisition system was used to continuously collect the data
During testing, the specimens were irradiated with the infrared lamps for 5 hours and then cooled to room temperature. The testing setup is shown in Fig. 2.

Figure 2. Thermal radiation simulation tests.

RESULTS AND ANALYSIS

Albedo test

The albedo results for all the pavement materials are presented in Table 1. It can be seen that the albedo of AC ($\alpha=0.05$) was the lowest among all materials. This was due to the black color of the AC’s surface, which endows it with a relatively high absorptivity of radiations. The PCC showed a higher albedo ($\alpha=0.27$) than that of PCPC specimen ($\alpha=0.13$), which indicates that PCC pavements could usually reflect more heat from the radiation source back to the atmosphere. This would negatively affect the UHI effect by increasing the discomfort level of the nearby humans and buildings.

Table 1. Albedo test results.

| Height of lamp/mm | Incident light intensity/ $\text{W} \cdot \text{m}^2$ | Reflection light intensity/ $\text{W} \cdot \text{m}^2$ | Albedo | Average value |
|-------------------|-----------------------------------------------|-----------------------------------------------|--------|---------------|
| PCC               |                                               |                                               |        |               |
| 300               | 1284                                          | 333.6                                         | 0.26   | 0.27          |
| 400               | 729.3                                         | 226                                           | 0.31   |               |
| 500               | 557.2                                         | 149.2                                         | 0.27   |               |
| 600               | 422.1                                         | 108.9                                         | 0.26   |               |
| PCPC              |                                               |                                               |        | 0.13          |
| 300               | 1284                                          | 161.7                                         | 0.13   |               |
| 400               | 729.3                                         | 96.4                                          | 0.13   |               |
| 500               | 557.2                                         | 69.7                                          | 0.13   |               |
| 600               | 422.1                                         | 51.3                                          | 0.12   |               |
| AC                |                                               |                                               |        | 0.05          |
| 300               | 1284                                          | 61.1                                          | 0.05   |               |
| 400               | 729.3                                         | 40.4                                          | 0.06   |               |
| 500               | 557.2                                         | 31.3                                          | 0.06   |               |
| 600               | 422.1                                         | 22.7                                          | 0.05   |               |
Simulation test results

Temperature variations in specimens

The surface and bottom temperatures of the specimens during testing are presented in Fig. 3. It is clearly shown that there were differences in temperature for different pavement materials, especially around the period with high thermal radiation intensity. The surface temperature of AC increased with a highest rate, while the PCPC and PCC exhibited relatively low increasing rate during the period of heating radiation. The peak temperature observed in the surface layer of AC was about 20% higher than that of the PCPC, and it was 30% higher than that of the PCC. This is mainly attributed to the differentiation of the albedo of the materials. The AC specimens had a lower albedo, so that they could absorb more heat from the radiation source and therefore presented higher surface temperatures.

It also can be seen that the PCPC could drop down to equivalent temperatures with the PCC soon after turning off the radiation source, which demonstrates that PCPC pavements could lose heat faster than PCC pavements during the temperature-fall period. From Fig. 3(b), it could be observed that the bottom temperature of PCC and PCPC were basically on the same level during the test. However, the surface temperature of PCPC was higher than that of the PCC, which indicates that PCC pavements have higher thermal conductivity and thermal convection than PCPC pavements. Thus, compared to PCPC pavements, PCC pavements are more inclined to absorb and store the heat energy from solar radiation, which shows negative impacts on the UHI effect.

\[ Q = C \cdot M \cdot \Delta T \]  
Eq. (2)
where, \( Q \) is the dissipated thermal energy, J; \( C \) is the specific heat capacity of the material, J/(kg·°C); \( M \) is the mass of specimen, kg; \( \Delta T \) is the variation of temperature during the testing process, °C.

The specific heat capacity represents the ability of the material for absorbing or releasing heat energy with a certain variation of temperature. Due to the difficulties to measure the specific heat capacity of pavement materials, the weighted average method was adopted in the study to approximately calculate the specific heat capacity of pavement materials by treating them as physically assembled composite materials with several components. Based on the previous study \(^{[16]}\), the following formula was used to calculate the weighted average specific heat capacity of the pavement materials:

\[
C_p = \frac{\sum C_i \omega_i}{\sum \omega_i}
\]  
Eq. (3)

where, \( C_p \) is the weighted average specific heat capacity, J/(kg·°C)

\( \omega_i \) is the weight of the component material, kg;

\( C_i \) is the specific heat capacity of component materials, J/(kg·°C)

The specific heat capacities of all the component materials used for the production of PCC, PCPC and AC are presented in Table 2, and with those results the specific heat capacities of those pavement materials can be determined.

**Table 2. Specific heat capacity of pavement materials at 30 °C, unit: J/(kg·°C).**

| Materials | Water | Cement | Aggregate | Sand | Asphalt | PCC | PCPC | AC |
|-----------|-------|--------|-----------|------|---------|-----|------|----|
| Specific heat capacity | 4175  | 838    | 745       | 757  | 1670    | 1025| 916  | 793|

The results of dissipated thermal energy for all the specimens are presented in Fig. 4. It is clearly seen that, during temperature-fall period, the PCC released more thermal energy than the AC and PCPC, which was 20% and 34% higher than that of AC and PCPC, respectively. This illustrates PCC pavements usually release more heat to the atmosphere at night (in the temperature-fall period), which is one of the major reasons that PCC pavements make negative contributions to the UHI effect.

**Figure 4. Dissipated thermal energy results of specimens.**
**Impacts on surrounding environments**

Fig. 5 illustrates the observed near surface air temperature above all specimens. It can be seen that the near surface air temperatures of the AC and PCPC were much lower than that of the PCC, which indicates that PCC pavements are more likely to increase the temperatures of its surrounding environments, and thus may cause more serious discomforts on human in the nearby residential areas.

**Figure 5. Near surface air temperature of specimens.**

**SUMMARY AND CONCLUSION**

Laboratory experiments were conducted to investigate the thermal properties of three types of pavement materials and their influences on UHI effect under laboratory-simulated conditions. Based on the study, the following conclusions can be drawn:

1) Due to the lower albedo and specific heat capacity, AC pavements usually absorb more heat and present higher surface temperatures than PCC and PCPC pavements under the same thermal radiation conditions. The surface temperature of PCPC is much lower than that of the AC and equivalent to that of PCC.

2) During the temperature-fall period (at night), PCC pavements could release more heat energy to the surrounding environments than AC and PCPC pavements, which is one of the major reasons that PCC pavements make contributions to the UHI effect.

3) According to the testing results, PCPC pavements would neither cause high thermal radiation nor release much heat to the surrounding environments. In addition, PCPC pavements could store much less thermal energy in daytime and release less heat to atmosphere at night.

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