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THE IN-SITU TEMPERATURE EVALUATIONS OF PERMEABLE PAVEMENTS IN SUMMER

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THE *IN-SITU* TEMPERATURE EVALUATIONS OF PERMEABLE PAVEMENTS IN SUMMER

Chen-Yu Hsu, Shih-Huang Chen, and Jyh-Dong Lin

Key words: permeable pavement, solar terms, great heat, heat output.

ABSTRACT

In this paper, one traditional asphalt and three permeable pavements were constructed to evaluate the thermal characteristics of pavement temperature at different depths and heat output in the field. The data were collected from May to July, 2011 to analyze with six traditional Chinese summer solar terms. On July 23, 2011 or Ta-Shu (great heat), it was the hottest day among six summer solar terms, while peak temperature of asphalt pavements was more than 60°C and ambient temperature was 36°C occurring at 14:00. In addition, it was found that reflectivity was affected by the color of pavement materials, and the thermal conductivity was influenced by the structural characteristics of pavements. The average heat output of grass bricks was found the least in comparison with others. Some heat outputs of porous asphalt concrete were larger than that of dense-graded asphalt concrete, especially from 16:00 to 21:00, but mostly were lower after midnight.

I. INTRODUCTION

"Heat Island" has been documented in European countries since 19th century and later studied in the United States in the 20th century. Most modern construction buildings and pavements absorb heat and retain energy from sun in urban or suburban areas more than the natural materials in rural area. For example, asphalt pavement is a dark and dry surface can reach up to 88°C (190°F) under the direct sun during the day, while the moist soil covered with grass may only reach to 18°C (70°F). In general, ambient temperature in urban below the height of tree tops and buildings can be higher than that in the rural area by 6°C (10°F) (Gartland, 2008). In addition, the concrete discharges internal temperatures slowly during the day and asphalt material releases surface heat faster than the concrete (Maria et al., 2013). Permeable pavements are designated for capture and treat the surface run-off. The infiltrated surface run-off will also help ground water recharge. Storm water can be hereafter reduced, retained, and stored in the pavement that is a sustainable process, especially suitable for urban areas (Andersen et al., 1999; Scholz et al., 2007; Wang et al., 2010).

The high conductivity of impermeable pavement material stores a large amount of heat during the day and subsurface heat storage is subsequently released to the atmosphere during the night. Hence, the air temperature is higher in the urban area than in the surrounding rural area not only during the day but also at night that causes the nocturnal urban heat island. Permeable pavement allows water to pass from the atmosphere to the soil in which the moisture evaporation can occur under the surface of pavement. Due to this evaporation, part of the net radiation is converted into latent heat similar to the phenomenon that occurs with a natural surface that covered by bare soil or vegetation. This means that the temperature of the permeable surface does not rise too much that subsequently reduces underground heat storage and heat exchange between the ground surface and the atmosphere (Asaeda et al., 2000).

The open air voids in permeable pavements increase the available surface area. This condition may limit heat transfer to the underlying soils in which it retains heat at the pavements surface (increasing daytime surface temperatures), but reduces bulk heat storage (decreasing nighttime heat release). The higher open surface area also increases the heat convection from ambient temperature to the pavement. In addition, the limited heat transfer of pavement tends to reduce the heat release during the night time as well. The heat release from urban materials is found significantly to contribute to the formation of nocturnal heat islands (US EPA, 2012).

Tan et al. (1992) proposed that the heat output into the environment above the pavement's surface can be estimated from the sum of the reflected, convection and emitted heats from the surfaces, as follows:

$$H_{reflect} = \rho \times I_0 \tag{1}$$

$$H_{convect} = h(T_{surf} - T_{air}) \tag{2}$$

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Table 1. Solar radiation properties for pavement materials (Tan et al. 1992).

Pavement Type	Estimated Solar Reflectivity ρ^a	Estimated Solar absorptivity α_s	Emissivity at 300 K ε^b	Published emissivity ε^c	Ratio α_s/ε
Asphalt Concrete	0.13	0.87	0.93	0.90-0.95	0.94
Interlocking Blocks	0.22	0.78	0.90	0.88-0.93	0.87
Terracotta Bricks	0.27	0.73	0.92	0.93-0.96	0.79
Granite Slab	0.30	0.70	0.90	0.88-0.95	0.78
Grass Cover	0.31	0.69	0.94	0.92-0.96	0.73

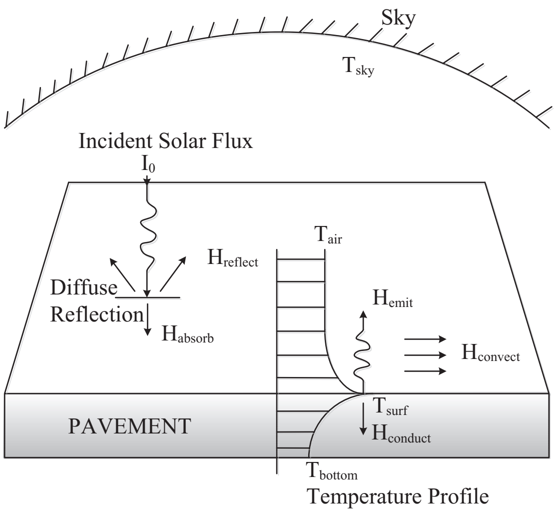

Fig. 1. Pavement surface heat transfer process (Tan and Fwa, 1992).

$$h = 5.7 + 3.8V \tag{3}$$

$$H_{emit} = \varepsilon \times \sigma \times (T_{suf}^4 - T_{air}^4) \tag{4}$$

$$H_{output} = H_{reflect} + H_{convect} + H_{emit} \tag{5}$$

where ρ = the reflectivity of the material, I_0 is the = solar influx (W/m^2), h represents = the average convection heat transfer coefficient, (W/m^{2}K), T_{surf} indicates = the pavement surface temperature (K), T_{air} is = the ambient air temperature. (K); V is the = wind speed (m/s); ε indicates = the emissivity of the pavement material; and σ is = the Stefan-Boltzmann constant with value of 5.67×10^{-8} W m^{-2} K^{-4}.

Eqs. (1) to (5) were suggested to obtain the heat output of pavement materials. Fig. 1 shows the heat exchanging process of pavement surface directly under the sun. In addition, Tan and Fwa (1992) also identified several reference thermal parameters related to different pavements and construction materials shown in Table 1.

II. EXPERIMENTAL PROGRAM

The objective of this study was to assess different types of permeable pavements by evaluating the field temperatures and thermal characteristics during the summer season in Taiwan.

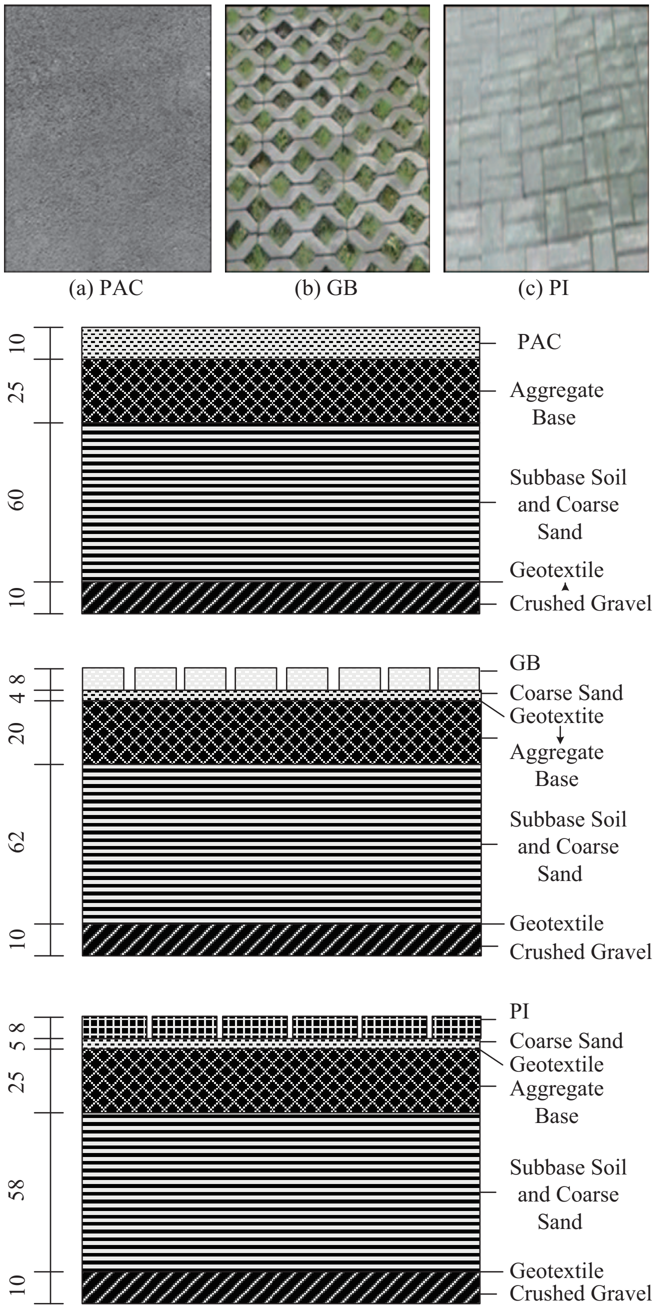

Fig. 2. Onsite photos and cross-sectional diagrams of the different permeable pavements.

1. Materials

A test site was identified at the Xindian district of New Taipei city in northern Taiwan. Three different permeable pavement materials, including porous asphalt concrete (PAC), grass bricks (GB) and permeable interlocking bricks (PI), were constructed in which each section of pavement was 3.85 meters long and 1.85 meters wide shown in Fig. 2. Underneath the surface course, there were 250 mm base materials with nominal maximum aggregate size of 19.5 mm. The subbase, about 600 mm in thickness, was compacted using the original soil blended with 50% (by weight) of coarse sand in order to increase the permeability. Below the subbase, it was designed and composed of the crushed gravel and geotextile with 100 mm in thickness to facilitate the infiltration of water. A comparative dense-graded asphalt concrete (DGAC) was also constructed and evaluated.

2. Instrumentations and Measurements

T-type thermocouples were utilized to measure pavement temperature including 0 (surface), 2 and 4-cm subsurface. Weather and meteorological data, such as ambient temperature, relative humidity (HD9007, Delta OHM), irradiation (LI-200SZ, LI-COR), solar radiation (LP NET 07, Delta OHM), and wind speed (CYG-3002, RM. YOUNG), were recorded (CR10X, Campbell Scientific). Data were collected every 10 minutes from May 6 to July 23 in 2011. In addition, thermal conductivity and reflectivity of each pavement materials were also evaluated. (ISOMET 2104, Applied Precision)

The traditional Chinese twenty-four "solar terms" designated by the lunar calendar were integrated into the data analysis. It includes six solar terms during the summer season in 2011:

(1) Li-Shia: beginning of summer (7th solar term)—May 6;
(2) Shiao-Man: grain full (8th solar term)—May 21;
(3) Mang-Chung: grain in ear (9th solar term)—June 6;
(4) Shia-Tzu: summer solstice (10th solar term)—June 22;
(5) Shiao-Shu: minor heat (11th solar term)—July 7; and,
(6) Ta-Shu: great heat (12th solar term)—July 23.

Multiple comparisons made with the least significant difference (LSD) method were performed to compare the significant differences between the six summer solar terms, and to comprehend the effect of various pavements on thermal changes. The calculation of heat output using Eqs. (1)-(5) was estimated from the sum of the reflected, convection and emitted heats for each permeable pavement.

III. RESULTS AND DATA ANALYSIS

1. Surface Temperature of Permeable Pavements Measured

Multiple surface temperature of pavements over six solar terms in the summer of 2011 were measured and compared. Fig. 3 shows the boxplots of surface temperature measured in a diurnal circle from six summer solar terms. The pavement temperature on July 23—the 12th solar term, or "Ta-Shu", was recorded the largest variation and highest peak in surface temperature of DGAC and PAC. The peak of pavement temperature in DGAC and PAC were more than 60°C, while the peak ambient temperature was about 36°C. It has to be noted that it was a rainy day on May 6, 2011 or "Li-Shia",

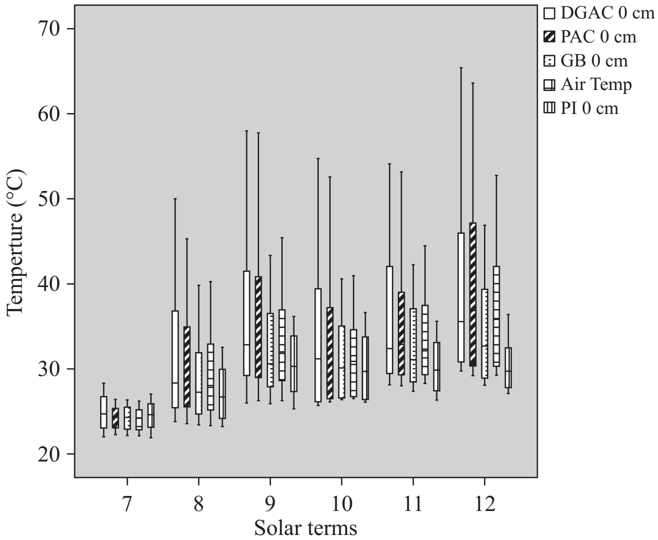

Fig. 3. Boxplots of multiple pavement temperature comparisons in different solar terms.

when every temperature measurements of pavements recorded more and less the same as ambient temperature, that was about 28°C. The examination on Fig. 3 reveals a trend in pavement temperatures rising with successive solar terms.

2. Fluctuation of Pavement Temperature at Great Heat Evaluated

Fig. 4 presents pavement temperature characteristics measured at different depths in a diurnal cycle on July, 23, 2011, or Ta-Shu: great heat. Temperatures at three different depths from the pavement surface top, namely 0, 2, and 4-cm, were measured. Each diurnal curve of pavement temperature exhibited fluctuating pattern: it started to arise on the surface on about 07:00 and on the subsequent 2 and 4-cm subsurface on about 08:00 and later; almost every temperature pattern reached the peak on about 14:00 and decreased to approach the asymptote during the midnight. The temperature measurements of DGAC, PAC, PI, and GB were fluctuating in 15, 10, 5, 3-°C in comparison of the peak values, respectively. The pavement temperature of DGAC increased rather steady than those of other pavements. The pavement temperature of GB covered with soil and grass was the least varying, while these of DGAC and PAC were fluctuating the most. At the depth of 4-cm, the peak temperature of PAC was 5°C higher than that of DGAC. A possible explanation of such phenomenon is that the solar flux or radiation penetrates deeper into the structural porosity of PAC that consequently increases the temperature at the underlying pavement.

3. Reflectivity, Thermal Conductivity, and Heat Output Assessed

Table 2 presents the reflectivity and thermal conductivity measured for each type of pavement material in this study. The results in reflectivity separated into two groups, namely

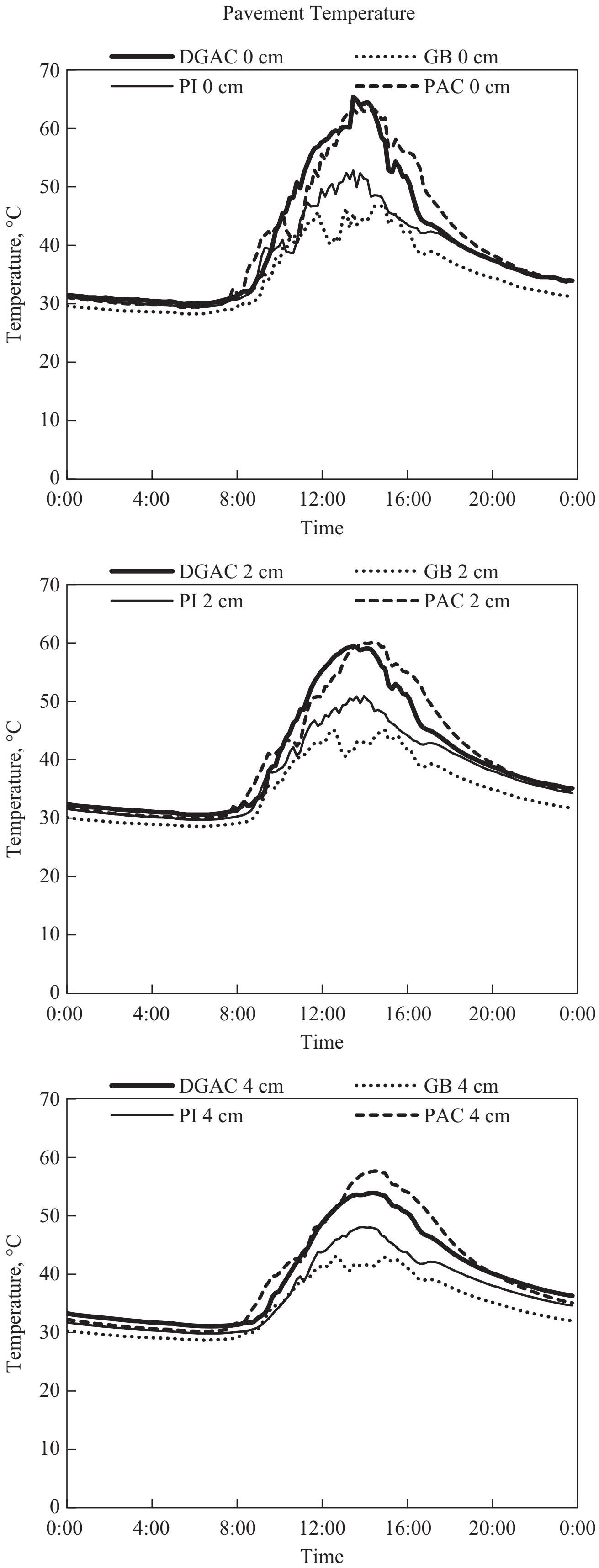

Fig. 4. Temperature fluctuation of pavements in a diurnal cycle.

Table 2. Reflectivity and thermal conductivity of pavements measured.

Thermal	DGAC	PAC	PI	GB
Reflectivity	0.05-0.1	0.06-0.13	0.14-0.2	0.14-0.22
Thermal Conductivity, W/mK	1.0-1.5	0.4-0.8	0.66-0.69	1.2-1.6

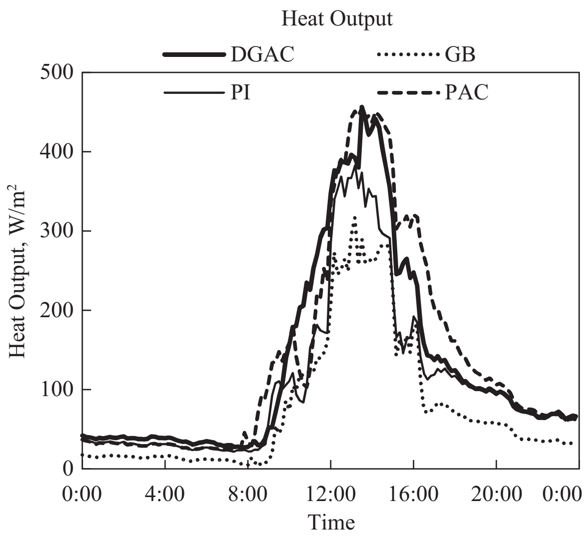

Fig. 5. Heat output at Ta-Shu: great heat in a diurnal cycle.

DGAC&PAC and PI&GB. The bituminous materials with black or quasi-opaque color in DGAC and PAC reflected about half in comparison with that in PI and GB that made by cementitious materials with brighter color. Another results indicate that the measured thermal conductivity of DGAC and GB were higher than PAC and PI. However, it is worthy to note that the thermal conductivity of GB was measured only on the compacted cementitious materials without evaluations on soil and grass components, which might indicate insufficient information was considered for the thermal properties on GB. However, it may imply that the dense-compacted materials, such as DGAC, is in fact capable of conducting more heats than that in porous mixtures, such as PAC or PI.

In addition, Fig. 5 organized the heat output calculated by Eqs. (1)-(5) on July 23, 2011 or Ta-Shu:great heat that analyzed the convection, emitted, and reflected heats. The mean heat output per ten minutes of DGAC, PAC, GB, and PI were assessed to result in approximately 188, 213, 114, and 148-W/m^2 during the day (from 05:20 to 18:40), while there were 80, 86, 44, and 80-W/m^2 during the night (from 18:50 to 23:50), respectively. It is clear that the heat output of GB was the least, followed by PI, DGAC and PAC. In addition, although some heat output of PAC were larger than that of DGAC, especially from 16:00 to 21:00, it was mostly lower than that of DGAC after midnight up to the sunrise. Similar trends can be found on the temperature fluctuation of pavements at different depths, when comparing DGAC and PAC.

IV. CONCLUSION

The overall assessment including the temperature fluctuation and the heat output of different pavement materials indicate that GB is the coolest pavement, followed by PI, DGAC and PAC in summer. However, there were several perspectives that are needed to investigate furthermore in the future. Firstly, there was no proper instrumentation on the underlying soil to measure the temperature in the base and subbase materials. The further investigation on temperature or heat conducted from the surface layer is needed. Secondly, there was not properly assessed on the effect of subsurface moisture evaporations and how it may affect the temperature fluctuation of pavements. It is suggested to assess the effect of moisture evaporation in temperature fluctuation in pavements. Thirdly, it was not able to measure the overall thermal conductivity of grass brick comprised of the compacted cementitious brick, soils, and grass. More endeavors on investigating the effective thermal properties of GB are necessary. Lastly, it was the pavement temperatures and thermal properties during six summer solar terms that were investigated and analyzed. However by past local experiences, it is sometimes hotter in fall. A rather longer time-span monitoring on pavement temperature across in summer and fall is highly suggested to fully assess the characteristics of pavement temperature and the heat output in the future.

Nevertheless, this study provides a good reference of comparing one traditional dense-graded asphalt concrete and three permeable pavements in assessing the fluctuation of pavement temperatures and calculated heat output in summer. The research findings are as follows:

1. Temperature characteristics of pavements over six summer solar terms, from May to July in 2011, were investigated. It was found that the peak temperature of each pavement at Ta-Shu: great heat was the highest. The peak temperature of DGAC and PAC reached more than 60°C, while the ambient temperature was about 36°C. The peak temperature of GB and PI were lower than that in DGAC and PAC at the same condition.
2. The DGAC, PAC, PI, and GB temperature measurements differed from their corresponding peak values by up to 15, 10, 5, and 3°C, respectively. The peak temperature occurred on about 14:00. Generally, the pavement temperature of DGAC and PAC were close to each other. At the depth of 4 cm, the peak in PAC was 5°C higher than that of DGAC. The possible explanation is that the solar radiation can penetrate deeply into the structural porosity of PAC and consequently increases the subsurface temperature.
3. Differences in reflectivity were found to depend on the type of material: bituminous or cementitious. DGAC and PAC that made of bituminous materials with black or quasi-opaque color reflected half in comparison with that in PI and GB that composed of cementitious materials with brighter color. The thermal conductivity of DGAC and GB (only the compartment of brick) with the dense structural mixture was higher than that in PAC and PI with porous structural mixture.
4. The heat output was assessed and calculated on July 23, 2011 or Ta-Shu (great heat). The average heat output every ten minutes of DGAC, PAC, GB, and PI were 188, 213, 114, and 148-W/m^2 during the daytime (from 05:20 to 18:40), while they were 80, 86, 44, and 80-W/m^2 during the night-time (from 18:50 to 23:50). The total heat output of GB was the least, followed by PI, DGAC and PAC. It was also found that some heat output of PAC were higher than that of DGAC in the afternoon, but mostly were lower after midnight. The same tread can be found in the temperature fluctuating of pavements at different depths.

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