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Experimental investigation on evaporation rate for enhancing evaporative cooling effect of permeable pavement materials

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HIGHLIGHTS

- A simple test method of evaporation rate was developed.
- Evaporation rate were measured for six permeable pavement materials.
- Main factors affecting evaporation rate were explored.
- Methods to enhance evaporation rate were proposed.

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ABSTRACT

Beyond the environmental function of stormwater management, permeable pavement is also a type of cool pavement that can help mitigate urban heat island effect through evaporative cooling. Evaporation rate is an important factor that influences the evaporative cooling effect of permeable pavements. A simple experiment method was used to initially explore the evaporation rates of different pavement materials under outdoor conditions. Experimental results of the evaporation rates were obtained for six different permeable pavement materials plus the bare water. The main factors influencing the evaporation rates were revealed. The findings imply that high water availability near the surface or large moisture exposure to the atmosphere are critical for the evaporation rate and consequent evaporative cooling effect of pavement materials. Increased air voids and permeability is one way to improve moisture exposure to the atmosphere and enhance the evaporation. Keeping the surface wet through enhanced capillary effect with finer gradations or directly sprinkling water on the surface is another way to produce a better evaporative cooling effect. An optimal design of materials with appropriately balanced pore size and capillary effect and adequate permeability is desired to maximize the evaporative cooling effect.

1. Introduction

1.1. Background

Cool pavement strategies can be used to mitigate urban heat island effects and improve outdoor thermal environments in urban areas. Improved outdoor thermal environments in urban areas could potentially help reduce the negative impacts of heat islands such as increased air conditioning (A/C) energy consumption of buildings and vehicles and impaired air quality (ground-level ozone) [1–10]. In addition, as a strategy to reduce Vehicle Miles Traveled (VMT) by creating livable and walkable communities, improving the street thermal environment is attracting increasing attention from practitioners, academics and competing industries [11–15]. Increased walking or cycling also provides an opportunity for improving human health and thus improving the quality of life [16,17].

With respect to the pavement type, the heat island might not just be a "black or white" issue (asphalt versus concrete, although it is known that albedo is a function of material microstructure and rugosity not just color), but also might be an "impervious and pervious" issue. To mitigate local heat islands and reduce the associated impacts mentioned previously, some impervious surface coverage can be substituted by pervious coverage. This is also the requirement for limiting disruption of natural hydrology according to LEED [18], which requires different options for project sites with impervious area greater or less than 50%. Permeable pavement, as

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a Low Impact Development (LID), can help minimize the impervious surfaces and could potentially improve the quality of life in a community and reduce other environmental impacts, such as reduced or at least slowed (where there is not full infiltration) stormwater runoff and associated water pollution, reduced stormwater management facilities, enhanced on-site infiltration for vegetation growth and recharging of underground water [1,2,19–24].

As one potential cool pavement type, permeable pavements have many environmental benefits beyond conventional impermeable pavements as mentioned above (note that asphalt, concrete and integrated concrete paver pavements can be considered for applications as permeable pavements). The main potential cooling mechanisms for permeable pavements are evaporative cooling [25,26], heat resistance [3,25,26] or reflection and evaporative cooling if using reflective permeable pavement [26,27].

Evaporation is energy transmitted away from the pavement surface by the latent heat of water vapor to achieve the phase change of water from liquid to gas. Water from moist soil or wet surface changes to vapor when heated by the solar heat or other heat sources. Water vapor then rises into the atmosphere, taking the solar energy with it and resulting in cooling effect. The evaporation term also includes evapotranspiration, a more complicated process plants use to keep cool. During evapotranspiration, water is drawn from the soil by the roots of the plant and is evaporated through stoma on the plant's leaves. Both evaporation and evapotranspiration increase when there is more moisture available, when wind speeds are greater and when the air is drier and warmer [28]. The evaporation latent heat loss q_{evap} (W/m^2) (i.e. theoretically maximum cooling effect) can be described as follows when water is completely exposed to air:

$$q_{evap} = L \cdot ER \quad (1)$$

where, *ER* is the evaporation rate; *L* is specific latent heat of water vaporization.

The evaporative cooling could reduce pavement temperature and consequent air temperature through latent heat absorbed during the phase change of water (from liquid to gas) when moisture exists in the pavement or in the underlying soil or is sprinkled on the pavement surface. Permeable pavements can provide these benefits. From the equation above, it is known that the latent heat loss (q_{evap}) from pavement is linearly and positively correlated with the evaporation rate (*ER*) for water exposed to air. The effect of evaporative cooling of permeable pavement highly depends on the evaporation rate of the permeable pavement materials [25,26]. Therefore, it is of great interest to explore and better understand the evaporation rate for different pavement materials used for permeable pavements.

1.2. Objective and scope of this study

The objective of this study is to measure and compare the evaporation rate of different pavement materials under outdoor conditions, and provide a better understanding and typical values of evaporation rate that are useful for the modeling and simulation of the cooling effect of evaporation from permeable pavements, and explore the first-order factors affecting the evaporation rate of permeable pavement materials.

2. Materials and methods

2.1. Description of test materials

The materials used for measurement of evaporation rate include water in six different pavement materials along with fully exposed water for comparison. These six pavement materials fall into two categories: permeable pavement surface layer materials and base layer materials or bedding layer materials. All these six types of materials are open-graded materials used in experimental pavement sections constructed at the University of California Pavement Center (UCPRC) test facilities in Davis, California.

A total of nine experimental pavement sections (A1–3, B1–3, and C1–3) were constructed for the cool pavement study at UCPRC. These nine test sections include three different pavement surfacing materials, namely integrated concrete pavers (surfacing type A), open-graded asphalt concrete (surfacing type B) and portland cement concrete (surfacing type C). For each pavement surface type, one impermeable pavement design (design 1) and two permeable pavement designs (design 2 and design 3, can also be referred to as porous or pervious depending on the material, the word permeable is used for convenience in this paper) were constructed. Six out of the nine sections are permeable pavements. Each section is 4 m by 4 m square in size (see Refs. [25–27,29] for more details).

Three permeable pavement surface layer materials were chosen for the evaporation testing in this paper, which are permeable asphalt B3 and permeable concretes C2 and C3. The permeable asphalt B2 is open graded asphalt concrete with a nominal maximum aggregate size (NMAS) of 9.5 mm and PG 64-10 asphalt binder. The main differences between permeable concrete C2 and C3 are the gradation and cement type. The C2 used a finer gradation with an NMAS of 4.75 mm and conventional gray cement, while C3 used a coarse gradation with the NMAS of 9.5 mm and a whiter cement. Due to the whiter cement with much lighter color, the C3 concrete sample has an albedo of 0.26 which is larger than that of 0.18 for the C2 concrete sample (see Table 1).

The three base layer materials or bedding layer materials include gravel S1 and S2 and sand S3. The gravel S1 was used as open-graded base aggregate reservoir layers in the six experimental permeable pavement sections mentioned above. The size of S1 is 19 mm. The gravel S2 is ASTM #8 aggregate (with NMAS of 12.5 mm, finer than S1) and was used as bedding layer materials for permeable paver sections A2 and A3. The gravel S3 is ASTM C33 sand (with NMAS of 9.5 mm, finer than S2) and was used as bedding layer material for impermeable paver section A1. In addition, a fully exposed water sample S0 was used for reference and comparison.

The gradations of these six materials are presented in Fig. 1. The C3 has the same NMAS as the B3, which is 9.5 mm. However, the C3 is more open-graded with more coarse aggregate compared to B3, as shown in Fig. 1. The gravel S1 is coarsest material followed by the S2 while the sand S3 is the finest material.

In addition to the gradation, the albedo, permeability, air void content and density of these materials were measured and listed in Table 1for reference (see Refs. [25,27,29,30] for details on measurements). The summary of each material along with material designs and other characteristics is listed in Table 1.

2.2. Experimental plan

The samples of these materials were put into 100 mm diameter × 150 mm height plastic cylinder containers (Fig. 2). The sample of permeable asphalt B3 was thin (60 mm), and the gravel S1 (19 mm NMAS) was used to fill up the cylinder (Fig. 2b) under the permeable asphalt B3, simulating the full permeable pavement structure (surface layer + reservoir layer).

Each dry sample and the cylinder container was then weighed together and recorded as m_1. The water was then added into each container slowly, ensuring it was filled up with water (Fig. 3). The permeable pavement or aggregate base will not be full of water and only partially saturated for most of time and regions. However, to simulate the permeable pavement just after the heavy rain event or extensive irrigation, the cylinders were first completely filled with water and allowed the water level to drop through evaporation. This will provide the opportunity of well monitoring the change of evaporation rate over time and better investigating the effect of water level on evaporation rate. The overflow and surface water was dried using a towel. Then the total weight of sample, container and water was measured and recorded as m_{20}. After that, the samples in containers were moved outdoors and placed under the sun for evaporation (Fig. 4). The total weight of each sample plus the container and remaining water was measured over time *t* and recorded as m_{2t}. The water weight left in the container at time *t* would be

$$m_{wt} = m_{2t} - m_1 \quad (2)$$

where m_{wt} is the mass (kg) of water left in the container at time *t*; m_{2t} is the total mass (kg) of a sample plus the container and remaining water at time *t*; m_1 is the total mass (kg) of a sample plus the container.

The weight loss (i.e. the water evaporated) over time *t* for each sample under outdoor conditions can be calculated as

$$\Delta m_{wt} = m_{20} - m_{2t} \quad (3)$$

where Δm_{wt} is the mass (kg) of water evaporated from the container at time *t*; m_{20} is the initial total mass (kg) of a sample plus the container and remaining water at time 0; m_{20} is the total mass (kg) of a sample plus the container and remaining water at time *t*.

The evaporation rate (*ER*, in kg/m^2/h or mm/h) during the time period t_1 through t_2 will be

$$ER = (m_{2t1} - m_{2t2})/[A(t_2 - t_1)] \quad (4)$$