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Water availability near the surface dominates the evaporation of pervious concrete

Yinghong Qin [a,b,c,*], Jacob E. Hiller [d]

[a] College of Civil Engineering and Architecture, Guangxi University, 100 University Road, Nanning, Guangxi 540003, China
[b] Key Laboratory of Disaster Prevention and Engineering Safety of Guangxi, Nanning 530004, China
[c] Key Laboratory of Disaster Prevention and Structural Safety of Ministry of Education, Guangxi University, Nanning 530004, China
[d] Department of Civil and Environmental Engineering, Michigan Technological University, 1400 Townsend Dr., Houghton, MI 49931, USA

HIGHLIGHTS

- Evaporation from pervious concrete is controlled by evaporative resistance.
- Evaporative resistance increases exponentially with decreasing water content.
- Wetting the pervious concrete keeps it cool for 12–24 h during hot summer days.
- Pervious pavement can be deemed as cool pavement unless it is rewetted in daily cycle.
- The best practice is to rewet pervious pavements around the noon time.

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ABSTRACT

In field trials of pavements, pervious concrete has been found to be both hotter and cooler than conventional concrete. There is much speculation on the cooling effect of pervious concrete, but specific measurements and modeling to confirm this are deficient. This study presents a model for the evaporation rate of pervious concrete pavements. The model is validated by the temperature observed from an experimental section and by documented data on the evaporation of pervious concrete. The model is then implemented into a one-dimensional pavement temperature model to simulate the temperature evolution of the pervious pavement system. It is found that the water availability (surface resistance) near the pavement surface dominates the evaporation rate of the pervious concrete. Rewetting the surface can keep the pervious concrete surface cool for 12–24 h during a typical hot summer day. After this period, the pervious concrete surface is hotter than a conventional concrete pavement. Rewetting the pervious concrete can keep it cooler than convectional concrete, especially when it is replenished with water around mid-day. Therefore, it should be cautious to deem pervious pavement as a cool pavement alternative unless it is re-wetted periodically.

1. Introduction

The process of urbanization typically removes natural grass and soil surfaces, replacing the ground with relatively impervious surfaces such as concrete or asphalt pavements, sidewalks, etc. Concrete surfaces are ready to absorb and store solar energy, which is released as sensible heat to the urban air contributing to the urban heat island (UHI) effect [1–5]. Pervious concrete has been advocated as a cool pavement option to battle UHI [4,6–8] because it can hold percolating water for subsequent evaporative cooling.

However, it has been long debated whether permeable pavements can stay cooler than traditional pavement types [7,9–12]. Some researchers have found that pervious concrete was as hot as traditional asphalt pavements on sunny summer days [9,10]. On contrary, others have found that a pervious pavement had lower temperatures at nighttime and could cool faster than normal concrete and thus may be deemed as a cool pavement [11,12]. The reasons for these conflicting results are that the evaporation of pervious concrete decreases during drying periods and that this decrease has not been fully understood. While some experiments on the evaporation of pervious concrete have been conducted under specific conditions [13–19], the evolution of the evaporation of pervious concrete after a rainy event has not been fully understood.

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* Corresponding author at: College of Civil Engineering and Architecture, Guangxi University, 100 University Road, Nanning, Guangxi 540003, China.

E-mail address: yinghong231@gmail.com (Y. Qin).

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This study models the evaporation from pervious concrete, using documented evaporation from a pervious concrete pavement section under controlled weather conditions. This model is then implemented into a one-dimensional heat transfer model to predict the evaporation during 10 continually-hot days. Simulations are conducted to study the evolution of temperature, evaporation, and water content of pervious concrete after wetting and to investigate the replenishment of water to foster evaporative cooling.

2. One-dimensional numerical heat transfer model and validation

2.1. Governing equations for the heat transfer at the pavement surface

The energy of an evaporable pavement surface is primarily driven by the solar radiation, I (W/m^2). This solar absorption can be partitioned into several factors including conduction G (W/m^2), convection H (W/m^2), long-wave emission L (W/m^2), and evaporation E (W/m^2) in the following equation:

$$(1-R)I = G + H + L + E \tag{1}$$

where R is the albedo of the pavement surface. These factors can be further refined to Eq. (2):

$$(1-R)I = k\frac{\partial T}{\partial z}\bigg|_{z=0} + h_c(T_s - T_a) + \varepsilon\sigma\left(T_s^4 - T_{sky}^4\right) + E \tag{2}$$

where T, T_s, T_a, and T_{sky} (K) are the temperatures of the ground, the surface, the air, and the sky, respectively; and k (W/(m K)) is the thermal conductivity of the pavement layers; z (m) is the vertical coordinate that starts from pavement surface with positive being downward; h_c (W/(m^2 K)) is heat convection coefficient; ε is the surface emissivity and σ is the Stefan–Boltzmann constant, 5.67×10^{-8} W m^{-2} K^{-4}.

The heat transfer between a pavement and underlying layers can be treated as a one-dimensional transient heat transfer in a semi-infinite body obeying Eq. (3):

$$c\rho\frac{\partial T}{\partial t} = k\frac{\partial^2 T}{\partial z^2} \tag{3}$$

where c (J/K) and ρ (kg/m^3) are the heat capacity and density of ground, respectively; t (s) is time.

Solving Eq. (3) requires knowing I, G, H, L, and E. The solar radiation I approximately follows a sinusoidal wave, with a peak at solar noon and zero at nighttime. It can typically be found from the local weather records.

For the heat convection $H = h_c(T_s - T_a)$, T_a is obtained from local weather data; T_s is solved by numerical iterations, and h_c can be reasonably estimated by [20]

$$h_c = 5.6 + 4.0v \tag{4}$$

where v (m/s) is wind speed measured at a height of 9.0 m.

For the long-wave emission, the sky temperature T_{sky} can be estimated by using Eq. (5) [21]:

$$T_{sky} = \varepsilon_{sky}^{0.25} T_a \tag{5}$$

Several models exist for estimating the sky emissivity ε_{sky}; and some calculate ε_{sky} using the air temperature, relative humidity, and sky cloudy factor [22,23]. As sky cloudy factor is difficult to quantify [24], the following equation can be used to compute ε_{sky} with reasonable accuracy

$$\varepsilon_{sky} = 0.754 + 0.0044 b_0\gamma/(a_0 - \gamma) \tag{6}$$

where $a_0 = 17.3$, and $b_0 = 237.7$, and $\gamma = a_0T_a/(b_0 + T_a) + \ln(RH/100)$ [25], here T_a has units of °C.

Evaporation from pervious concrete is the subject of moisture and heat transfer in porous media [26–28]; modeling these factors requires parameters including the gas permeability, conductivity, vapor permeability, and moisture diffusivity, and others [29]. For pervious concrete, most of these parameters remain unknown [30]. But as a porous material, the evaporation of a pervious concrete sample can be analogized to that of moist soil. This evaporation is strongly governed by the moisture availability at the surface. According to [31], the evaporative flux obeys Eq. (7):

$$E = \lambda\frac{\rho_a - \rho_{sat}}{r_s + r_a} \tag{7}$$

where λ is the enthalpy of vaporization of water, 2260×10^3 J/kg; ρ_a (kg/m^3) is the density of humid air; ρ_{sat} (kg/m^3) is the density of saturated vapor air; r_a (s/m) the aerodynamic resistance; and r_s (s/m) expresses the surface resistance.

r_s represents the resistance of detaching the saturated water from the concrete matrix to the internal pores, while r_a represents the resistance of transporting the pore moisture to the ambient air. The surface resistance can be computed by [31]:

$$r_s = ae^{b\theta} \tag{8}$$

where a (s/m) and b are two regressed constants, θ (%) is the water content. a, b, and θ will be parameterized in Section 2.2.2.

Many models provide sufficient accuracy for the aerodynamic resistance [32] but need many input parameters. A simple, semi-empirical equation [33] provides reasonable accuracy and needs only the wind speed as its input. In this study, this simple model is used to estimate the aerodynamic resistance, as shown in

$$r_a = K/v \tag{9}$$

where wind speed v is set as 0.5 m/s when $v < 0.5$, $K = 208$ is recommended for coarse dry soil below the canopy. The value of K at a pervious concrete surface remains unknown and will be calculated in Section 2.2.2. Therefore, the bulk evaporative resistance is

$$r = ae^{b\theta} + K/v \tag{10}$$

In Eq. (7), the density of humid air ρ_a can be estimated as:

$$\rho_a = (p_dM_d + p_vM_v)/(RT_a) \tag{11}$$

where M_d is the molar mass of dry air, 0.029 kg/mol; M_v is the molar mass of water vapor, 0.018 kg/mol; R is the universal gas constant, 8.314 J/(K mol); p_d (Pa) is the partial pressure of dry air; p_v (Pa) is the vapor pressure of water;

$$p_v = p - p_d \tag{12}$$

$$p_d = p - \phi\, p_{sat} \tag{13}$$

where p is the local atmospheric pressure (e.g., $p = 101{,}325$ Pa at sea level); ϕ is the relative humidity; and the saturated vapor pressure p_{sat} (Pa)

$$p_{sat} = 6.11 \times 10^{7.5T/(T+237.3)} \tag{14}$$

In Eq. (14), the temperature T is defined as the mean temperature of 1.0 cm of topsoil [34]. In this study, the average temperature at top 1.0 cm of a pavement is deemed as the temperature, T, in Eq. (14) because the near-surface temperature of a pavement varies similarly as topsoil temperature.

2.2. Validations of the models

2.2.1. Validations for the prediction of a dry-pavement temperature

We first validate the numerical model with ten-day temperature series that were observed at different depths at an experimental concrete pavement in Davis, California. Details about the experimental setup of this section can be referred to [35].