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Hydrological properties and solar evaporative cooling performance of porous clay tiles

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HIGHLIGHTS

- We assessed the water absorption properties of a porous clay tile.
- A wind tunnel apparatus provides reliable environment control.
- A porous clay tile composite shows good solar evaporative cooling performance.

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ABSTRACT

Evaporative cooling from porous building materials is one of the passive strategies used for building energy conservation. In this study, a porous clay tile (PCT) with specific pore size and porosity characteristics was selected as water storage medium. A composite construction, comprising the PCT, a waterproof coating, a cement mortar layer, and a base layer, was manufactured and its performances as an evaporative cooling structure were evaluated. First, the water absorption properties of the tile were characterized using a partial immersion test, from which the water absorption coefficient and the capillary water content were determined. The solar evaporative cooling performance of the composite construction was then investigated using a special wind tunnel, which allowed controlling the temperature, relative humidity, wind velocity, and simulated solar radiation conditions. The porous clay tile exhibits a relatively high water absorption rate, with a water absorption coefficient of 0.3286 $kg/m^2 \cdot s^{0.5}$. Although the water retaining capacity of the tile (as represented by a capillary water content of 168.7 kg/m^3) was not outstanding, the composite construction still produced significant evaporative cooling when water was applied on the PCT. In cyclic experiments performed inside the wind tunnel, the energy balance analysis revealed that, even though the shortwave radiation absorbed by the surface of the wet specimen was larger than that absorbed by the dry specimen surface, 80% of the radiation absorbed by the wet specimen was transformed into latent heat flux, which decreased the external surface temperature by up to 11 °C and reduced the internal surface heat flux by 67.7%.

1. Introduction

Evaporative cooling from the external surfaces of pavements or buildings has attracted increasing attention in recent years. On an urban scale, numerous experimental and simulation studies have shown that evaporative cooling from water-retaining or water-permeable pavements can reduce the urban temperature, thus mitigating urban heat island effects [1–6]. On a building scale, evaporative cooling from porous building materials is based on the evaporation of stored water during the hotter hours of the day, which leads to a decrease in the temperature of the porous surfaces due to the latent heat released. The lower surface temperature contributes to reducing building cooling loads, because the amount of heat transferred through the external surface to the interior of the building is reduced [7–10].

Both modelling and experimental approaches are currently being applied to study the evaporative cooling of porous materials. The former generally involve mathematical models [11,12] or empirical equations [13] to describe the heat and moisture transfer

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phenomena that take place during the evaporation process. Compared to modelling studies, a larger number of experimental studies have appeared in the literature. Qin et al. developed a new simple apparatus to measure the gas permeability of pervious concrete, which is an important parameter for determining the soil breathing under pervious pavements. Their apparatus was assembled to allow gas flowing through a pervious concrete sample under steady pressure conditions. A vacuum was used to create a stable gas flow through the sample while the gas flowing rate was gauged by a Venturi tube. The gas permeability was measured under different applied pressures and saturation conditions [14]. Zhang et al. conducted a comparative analysis to investigate the energy saving rate of an evaporative cooling wall that used porous clay tiles (PCTs) as exterior decoration. In their study, two rooms with the same construction features, orientation, and dimensions were tested and the results showed that the air conditioning power consumption of the room decreased by 35.29–68.27% upon water application on the external surface [7]. Li et al. reported that the evaporation rate is an important factor affecting the evaporative cooling effect of permeable pavements. They used a simple experimental method to explore the evaporation rates of six different permeable pavement materials and of bare water under hot summer outdoor conditions. Their experimental study revealed that high water availability near the surface or large moisture exposure to the atmosphere are critical for the evaporation rate of pavement materials, as well as the high air temperature and low humidity [15]. Pires et al. compared the water absorption and evaporative cooling characteristics of six types of building materials and five types of textile fabrics. Their study included two different tests. The samples were first immersed into a water bath until they reached water saturation, and then dried in a small wind tunnel at different wind speeds and temperatures. As far as the water absorption and evaporative cooling characteristics were concerned, the experimental results showed that the best performances were achieved with ceramic hollow bricks and textile fabrics. The authors eventually selected a sample made of polyester fabrics with honeycomb cavities for further investigation in a subsequent evaporative cooling study [16]. Wanphen et al. investigated the moisture and thermal performance of four kinds of materials (pebbles, silica sand, volcanic ash, and siliceous shale). A controlled environment chamber with highly stable air temperature and relative humidity conditions was used to carry out the evaporation experiments. In order to keep the surface of the samples under fully developed wind flow and avoid vertical convection effects, a wind tunnel apparatus was placed inside the chamber. Additionally, a metal halide lamp located above the removable glass cover on top of the wind tunnel was used to simulate the solar radiation. The results of the tests indicated that porous materials can effectively reduce the surface temperature, up to a degree that is closely related to the moisture content of the material, its absorption coefficient of solar radiation, the wind speed, and the evaporation rate [17].

The main limitations of the previous experimental studies are the following: (1) some of the systems investigated may have limited application in real buildings. For example, although the polyester fabric with honeycomb structure exhibits desirable water absorption and evaporation properties, it is difficult to use this material on the surface of a building to achieve evaporative cooling, due to its weak mechanical strength; (2) some studies have indicated that the water absorption rate and water retaining capacity of porous building materials have a significant influence on the evaporation performance. However, not many studies have quantitatively assessed the water absorption properties of porous building materials for evaporative cooling purposes; (3) the wind tunnel is a powerful experimental device, not only for aerodynamics research but also for thermodynamic studies of porous materials, and has been used to investigate the heat and moisture transfer process in porous materials under steady state or dynamic experimental conditions. However, limited information was provided about the details of the apparatus employed, such as its environment control system and the corresponding accuracy.

Taking into account these limitations, the goals of this work are as follows: (1) quantitatively assessing the water absorption properties of a porous clay tile, which represents a common decoration product in the building materials market; (2) introducing a special wind tunnel apparatus and evaluating the accuracy of its environmental control system; (3) using the wind tunnel to investigate the solar evaporative cooling performance of a composite construction, in which the PCT is employed as water storage medium. The rest of the article is organised as follows: section 2 describes the materials and methods employed; section 3 presents the analysis of the water absorption properties of the porous clay tile, examines the accuracy of the environment control system of the wind tunnel, and illustrates the thermal behaviour of the composite construction in wind tunnel cyclic experiments. The results are also discussed in this section. Finally, the main conclusions are summarised in section 4.

2. Materials and methods

2.1. Materials

The materials employed in this study comprise a porous clay tile and a composite construction consisting of the tile, a waterproof coating, a cement mortar layer, and a base layer.

2.1.1. Porous clay tile

A porous clay tile (240 mm length × 50 mm width × 10 mm thickness) was selected for the present study, since these tiles are frequently used as decoration layer on the exterior surface of building envelopes (roofs or walls), and their evaporative cooling performance has been demonstrated [7]. The morphology of the tile surface was studied using a tungsten filament scanning electron microscope (SEM, Fig. 1). The figure reveals a relatively large number of pores of rather large size (2.0–6.0 μm) on the tile surface. The internal pore size distribution of the tile was examined using the mercury intrusion method (Fig. 2), which revealed a porosity of 27.34%, a corresponding saturated mass water content of 13.81%, a specific surface area of 0.20 m^2/g, and a mean pore size of 3.967 μm. These characteristics are suitable for water absorption and storage, and at the same time would not significantly reduce the mechanical strength of the tile.

2.1.2. Composite construction

The PCT was used as water storage medium, due to its favourable pore characteristics. In order to reduce the negative influence of moisture migration, we set a waterproof coating between the tile and the cement mortar layer. The base layer was fabricated using concrete. To reduce the impact of water absorption by (and

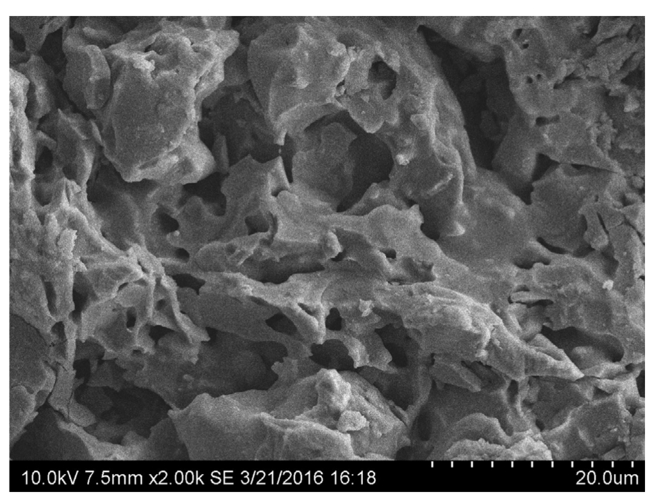

Fig. 1. SEM image of the porous clay tile examined in this study.