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Multivariable analysis of potential evaporation from moist asphalt mixture

Alvaro Garcia *, Abdushaffi Hassn, Andrea Chiarelli, Andrew Dawson

Nottingham Transportation Engineering Centre, School of Civil Engineering, University of Nottingham, University Park, Nottingham NG7 2RD, UK

HIGHLIGHTS

- The air voids distribution of asphalt mixture has been characterized.
- Water evaporation has been correlated to the air voids properties.
- The main factors affecting water evaporation from asphalt roads have been identified.

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ABSTRACT

Asphalt pavements are normally dark colored and may get a very high temperature difference with the environment during daytime, but the influence of water evaporation in their temperature is unknown. Water evaporation experiments have been conducted using asphalt mixture with various air voids contents while monitoring the surface temperature and heat flux. It was observed that a relationship exists between the evaporation rate, the heat flux, and the surface temperature during water evaporation. In addition, the evaporation rate has been related to air voids parameters such as air voids content and diameter, tortuosity, or the Euler number.

1. Introduction

Water evaporation from porous media is a fundamental engineering problem that has influence in fields such as food processing [1], agriculture and environment [2,3], and construction technology [4]. Moreover, water evaporation can be used to control the urban heat island (UHI) effect by reducing the temperature of pavements [5] and building facades [6]. Much research has described the drying behavior of porous media [7,8], which is normally characterized as a two stages process. In Stage 1, evaporation is limited by the atmospheric conditions and water is supplied by a capillary flow that connects the receding drying front to the evaporating surface. Between the evaporation surface and the drying front lies a capillary fringe with continuous saturated capillary channels connecting the two [7], even though the overall saturation of this fringe is less than 100%. For a porous material experiencing evaporation from its top surface (such as a soil or pavement), when the drying front reaches a given depth, the downward gravity and viscous forces overcome the capillary force, and the water supply for evaporation by absorption of latent heat is stopped [9]. The disruption of the capillary flow marks the beginning of Stage 2, which is characterized by a lower evaporation rate and is limited by diffusion through the porous media [10]. During this stage, the location of evaporation shifts from surface to sub-surface, resulting in the formation of a dry layer where only vapor flow occurs [11]. This affects the total flux of energy through the material, as the energy that before was directly used for evaporation, will have to be transported from the surface, through the material to reach the drying front [12]. Transition from evaporation Stage 1 to 2 in porous media is controlled by the pore size distribution [13], capillary length [9], material wettability [14] and capillary pressure [15]. Moreover, it is known that capillary pressure at constant degrees of saturation decreases as temperature increases [16].

Most of the previous studies on the dynamics of water evaporation have considered evaporation only at the environmental, constant, temperature, which is not representative of the real world evaporation in soils or construction materials, as these may reach higher temperatures than the environment due to their dark color [17].

* Corresponding author.
E-mail address: alvaro.garcia@nottingham.ac.uk (A. Garcia).

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The motivation of the paper is to obtain complete dynamic information on the water evaporation process from an asphalt surface during a continuous drying event that includes both Stages 1 and 2. With this purpose, asphalt mixtures with air contents ranging from 4% to 26% were manufactured, and observations relating the time dependent evaporation rates of saturated asphalt mixtures were compared to the development of a number of parameters, such as asphalt surface temperatures during heating, heat flux, porosity, and thermal conductivity. In addition, the air voids configuration was characterized and their properties, e.g., Euler number, tortuosity, diameter of air voids, and macroporosity, were compared the parameters mentioned above. The authors expect that these results will have a strong impact on the design of asphalt mixtures to minimize the pavement contribution to the urban heat island effect and on the design of new types of asphalt solar energy collectors such as those described in [18,20].

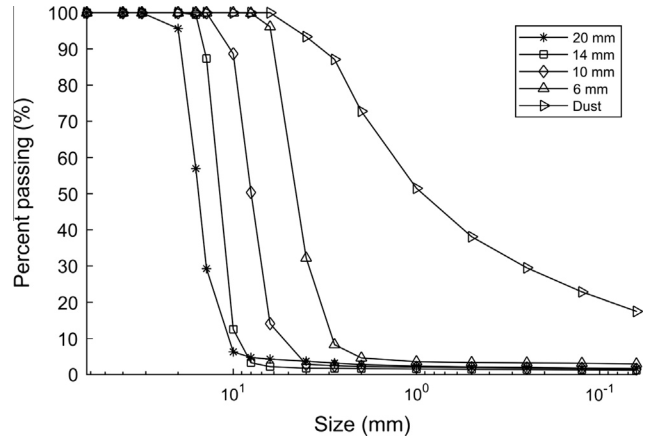

Fig. 1. Aggregates gradation.

2. Experimental method

2.1. Description of materials

Six asphalt concrete slabs were used to measure the evaporation rate (each 306 × 306 × 50 mm). The samples were produced using a 60/40 penetration grade bitumen binder and 20 mm maximum limestone aggregate size, mixed at 160 °C, and compacted at 140 °C to the target air voids of 4.5%, 10.0%, 13.0%, 17.0%, 21.0%, and 26.0% using a roller compactor (see Table 1 to know the aggregate gradation for every asphalt mixture analysed). In addition, the gradation curves for each type of aggregate used are shown in Fig. 1.

2.2. Density

Asphalt mixture density was determined according to BS EN 12697, part 5 (2009) [21] by the mathematical method. In addition, the bulk density of the test specimens was determined according to BS EN 12697, part 6 (2003) [22] by the dimensions method from the average of three test specimens for every asphalt mixture type analysed.

2.3. Air voids content (AVC)

The air voids content of the asphalt mixtures was calculated based on the maximum and bulk densities. The percentage of air voids in the mixture can be calculated as:

$$V_m = \frac{\rho_m - \rho_b}{\rho_m} \times 100\%. \tag{1}$$

where ρ_m is the theoretical maximum density of the mixture without voids, measured in kg/m^3, ρ_b is the bulk density in the mixture, measured in kg/m^3, and V_m is the air voids content in the mixture, expressed as a percentage.

2.4. Experimental setup and measurements

The experimental setup is illustrated in Fig. 2. First, the mass of every slab was recorded using a digital balance (Ohaus Ranger 3000). Then, asphalt slabs were saturated by placing them under water for 12 h. Later, the saturated asphalt concrete slabs were placed into a 310 × 310 × 50 mm rectangular acrylic transparent box (i.e. with a 2 mm gap on the four vertical edges). The acyclic box was then placed on a digital balance (Ohaus Ranger 3000), which has a capacity of 15 kg and a resolution of 0.005 kg. Finally, more water was added to the slabs until the box was completely filled just covering the top of the asphalt.

Table 1
Composition of asphalt mixture.

Target air voids	4.5%	10.0%	13.0%	17.0%	21.0%	26.0%
Sieve size (mm)	Cumulative aggregate Weight % retained					
28.0–20.0	20	20	20	20	10	20
20.0–14.0	40	43	45	51	48	80
14.0–10.0	55	63	71	76	83	90
10.0–6.3	70	74	78	81	83	90
Dust (<6.3 mm)	100	100	100	100	100	100
Bitumen (% of Weight of mixture)	5.1	4.5	4.2	3.8	3.5	3.2

Each asphalt concrete slab was placed under a heat source for 16 h. Four 250 W infrared lamps were used as the heat source. The infrared bulbs were placed at 730 mm from the samples (see Fig. 2). The digital balance was then continuously monitored to determine the mass reduction rate during the experiments.

2.5. Heat flux and temperature measurements

An ITI model GHT-2C Geothermal Heat Flux Transducer with a size of 50.8 × 50.8 mm^2 and a height of approximately 4.8 mm was used to measure the heat conducted through the asphalt concrete slabs. The sensor is a water-proof meter, with a nominal sensitivity of 5 W/m^2 mV, a temperature range of −38 °C to +121 °C and an accuracy of 1%.

The transducer was embedded into the bottom of the acrylic box in order to have good contact with the asphalt concrete slabs. The sensor measures the heat flux as a DC voltage generated by the temperature difference between its top and bottom surfaces. This voltage is proportional to the local heat flux and it was digitally recorded for all the experiments performed.

The surface temperature of the asphalt concrete slabs was measured by using a J-type thermocouple placed in the geometrical center of the slab. The temperature profile was recorded for 16 h with a constant environmental (air) temperature of 25 °C ± 2.

The heat flux meter and the thermocouple were connected to a data logger (Omega OMB-DAQ-54) that allowed measurements at 1 min intervals.

2.6. X-ray computed tomography (CT scans)

In order to have an indication of the internal structure of the asphalt mixtures evaluated, X-ray tomography on different samples has been employed.

The X-ray micro tomography scans were carried out on the micro computed tomography facility at the University of Nottingham. The X-ray source was operated with an acceleration voltage of 290 kV and a current of 1.55 mA. The sample was mounted on a rotational table in a distance of 50 cm from the X-ray source. The pixel size obtained was 65.2 μm.

The images were processed with the commercially available Materialise Mimics and the open source software ImageJ Version 1.49 [23], the images were converted to 8-bit grayscale resolution and cropped to a region of interest (ROI) of 8 cm × 8 cm × 6 cm. Reconstructions of the microstructure were prepared by segmenting the materials found in a specific volume, based on grayscale thresholding. With this simple method, aggregates, bitumen and air voids could be readily separated. The thresholded images of the air voids were stacked with the software Materialise Mimics. Each pixel in the porous space can then be connected to 26 other pixels around it (alongside, above, and below), which are called neighboring pixels. Therefore, it is possible to generate surfaces that encase each group of neighboring pixels belonging to a common void space.

As it is known that small isolated clusters of void or grain voxels may correspond to small isolated pores or to noise effects [24], these were removed from the image prior further analyses. All features smaller than 2 voxels in width (minimum Feret's diameter <0.5 mm) were removed from the segmented binary data to prevent their classification as pores.

2.7. Topology of air voids

The macropore characteristics that were quantified based on CT Scans included air voids content, mean macropore thickness, connectivity and tortuosity (T). These are commonly used properties to analyse the topology or soils and porous media [25].