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Wetting and drying in hydrophobic, macroporous asphalt structures

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HIGHLIGHTS

- Gravity-driven wetting and forced convective drying of porous asphalt (PA) is investigated.
- Water droplets show high penetration only in PA specimens with pores of diameters 2–6 mm.
- Due to the strong influence of gravity, water retention is only near the bottom region.
- Large vapor diffusion length observed in PA specimens.
- Limited effect of airflow as a result of the large vapor diffusion length.

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ABSTRACT

Wetting and drying of a hydrophobic, macroporous medium like porous asphalt (PA) are investigated in this study under different environmental loadings. Three different types of porous asphalt, PA4, PA8 and PA11, with different pore size distributions, are used to produce specimens that are sealed on all sides except at the top surface, and are wetted by discrete water droplets or by pouring water from the top. The wet specimens are subjected at the top surface to airflow, at low (1 m/s) or high (3 m/s) wind speeds, and heat from a UV lamp. Gravity-driven imbibition by impinging water droplets is observed only in PA11 specimens due to the presence of large pores with diameters between 2 and 6 mm. However, the drying patterns of all the three types of PA are similar i.e. even after 3.5 h of forced convective and non-isothermal drying, water evaporates only near the top surface. The hydrophobicity of the solid matrix limits the influence of liquid transport on the drying process. Consequently, the dominant drying mechanism found in PA is evaporation at the free surface of water islands within the specimen, followed by water vapor diffusion to the top surface and its subsequent convection by airflow. Therefore, high wind speeds lead to a faster drying only if moisture is concentrated near the top surface of the specimen. In comparison with a previous experiment, it is seen that in PA8 and PA11 specimens, gravity-driven drainage is the most important source of fast moisture removal and has a much shorter time-scale than convective drying.

1. Introduction

The durability of several porous materials used in the built environment such as concrete, sandstone, limestone, brick, asphalt etc. is highly dependent on the residence time of water within these materials as water is their main agent of degradation. Many types of rocks, soils and building materials are macroporous structures (defined here as materials with pore sizes larger than 0.1 mm) and, hence, transport behavior in macroporous media deserves more attention as most of the existing literature is focused on microporous media. For instance, in macroporous media, the relative importance of the different liquid and gaseous transport phenomena such as gravity-driven drainage, capillary flow, gaseous

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diffusion, evaporation and forced convection are expected to be significantly different than what is seen in microporous media.

A good example of a material that undergoes moisture-induced deterioration is porous asphalt (PA). PA is a composite, macroporous material used as the surface layer of roads to allow the drainage of water and thereby prevent aquaplaning and splash-spray effects during and after rain events. PA has a porosity of approximately 20% and is a composite material made from fine and coarse mineral aggregates, a bituminous binder and air voids. A detailed description of a typical microstructure of PA is given in [1]. Due to the high permeability of PA, its internal structure is significantly exposed to water. Therefore, PA is more susceptible to moisture-induced deterioration than dense asphalt concrete, resulting in a shorter service life [2]. Water induces deterioration in PA primarily by affecting binder cohesion and the adhesion between binders and aggregates [3]. Consequently, it is important to analyze the residence time of water in PA under different wetting and drying conditions since it is directly related to its durability. The most important environmental loads on PA are wetting by rain, forced convective drying by airflow and thermal drying by solar radiation. Studies that have combined imbibition, forced convective drying and thermal drying in PA or other porous media are scarce in literature, although these mechanisms have been extensively analyzed individually.

Experimental investigation of imbibition in porous media has been undertaken by various researchers [4–7]. Transport phenomena such as gravity-driven flow paths [8,9], dynamic front movement [10] etc. have been studied through experiments and imaging. The minimum and maximum sand particle diameters in the experiments of [10] were 75 and 200 μm respectively. Yoon et al. [11] used magnetic resonance imaging (MRI) to investigate water flow through five layers of natural quartz sand fractions, the coarsest of which (Accusand Grade 12/20) had minimum and maximum particle diameters of 0.85 and 1.7 mm respectively. Shahraeeni et al. [12] investigated the nonlinear nature of evaporative coupling between drying porous media and air boundary layer under wind speeds of 0.75–4 m/s and particle size diameters of 0.3–0.9 mm. However, to the best of our knowledge, no study has been performed on imaging water movement within macroporous media with pore sizes in the range of millimeters, as in the case of PA. Another factor that can potentially influence gravity-driven imbibition in macroporous media is the wettability of the solid matrix. Bauters et al. [13] reported the drying and wetting behaviors of partially hydrophobic soil subjected to gravity-driven imbibition. The maximum particle size was 0.15 mm. During drying, air entry pressure decreased from -7 cm for the hydrophilic sand to -20 cm for all the partially hydrophobic sands. During wetting, water entry pressures increased with increasing hydrophobicity. Surface roughness has also shown some influence on gravity imbibition at near-zero matric potentials [14]. However, its influence in a macroporous medium is expected to be not very significant.

Forced convective drying of porous media is a coupled heat and mass transfer process influenced by the surrounding conditions as well as the hydraulic conductance and vapor diffusivity of the material. Forced convective heat and mass transfers have been studied for various scales of porosity, ranging from microporous media [15] to highly porous macroporous media [16] and variable-porosity media [17]. For a porous medium with pore sizes < 1 mm undergoing evaporative drying in typical natural airflow conditions (mean wind speed < 4 m/s), Haghighi et al. [18] found that considering only diffusion from individual pores across a constant boundary layer accounted for most of the evaporation predicted by the full advection–diffusion equation. In a macroporous material with pore sizes larger than 1 mm and with a complex pore space geometry, the relative contributions of diffusion and advection to the total moisture loss from the material is an aspect which needs to be investigated. Reis et al. [19] was the first to investigate droplet penetration into porous media and subsequent drying by forced convection. Their porous media were sand particles of 180 μm and glass beads of 50, 120 and 400 μm. For sand particles, they found that capillary diffusion of water to the top surface played an important role in the evaporation process. Reis et al. [20] investigated droplet penetration in porous media and subsequent drying by forced convection at different airflow speeds. They embedded a single diethyl-malonate (DEM) drop-let of 2.3 mm diameter into a porous substrate consisting of 120 μm glass beads. They concluded that although liquid expectedly evaporated faster at higher airflow speeds, the resistance of the porous medium to evaporation was very high. However, it needs to be investigated if the limiting effect of the porous medium to evaporation of the liquid within it is as strong in the case of macroporous media where significant air penetration into the medium can be expected. Poulikakos et al. [21] carried out neutron radiography investigations of forced convective drying in new and aged PA11 specimens at a wind speed of 2.4 m/s. Drainage was completely blocked. They postulated that drying was relatively faster as long as water distribution within the specimen was well-connected. Jerjen et al. [22] investigated the drying rate of PA8 cores of 30 mm diameter and 67 mm height, using X-ray micro computed tomography (X-ray μ-CT). 26 three-dimensional X-ray μ-CT scans were obtained over a scanning time of 57 h. They observed sudden drops of the total water content in PA due to accelerated moisture loss at two sites. The complex drying mechanism of PA was effectively brought out by their experiments.

Solar radiation is another factor that can influence evaporation in a porous medium exposed to environment. On one hand, solar radiation can accelerate drying by providing the latent heat required for evaporation while on the other, thermal gradients within the porous medium can facilitate redistribution of water from the pores to the surface [23–27]. In a macroporous media with pore sizes large enough for gravity to dominate over capillary force, it remains to be investigated what is the influence of a temperature gradient on the liquid redistribution and drying processes. Another open question is to determine if thermal gradients, which develop due to evaporative cooling, influence the drying process in macroporous media.

In light of the studies mentioned above, the specific objectives of this study are (i) to understand the wetting process in dry PA specimens, (ii) to analyze the effects of turbulent airflow above the surface and a temperature gradient on the drying process and (iii) to correlate the observed wetting and drying behaviors of PA specimens to their pore space characteristics. We use neutron radiography (NR) imaging to obtain the spatial and temporal distributions of moisture content in PA. The three-dimensional pore space of the specimens is visualized with X-ray μ-CT. In the next section, first the characteristics of the specimens investigated in this study are presented, followed by a brief description of the imaging techniques used and the details of the experimental procedure. We then analyze the wetting and drying processes in PA, study the influences of various parameters on the wetting and drying processes and present our conclusions.

2. Materials and methods

2.1. Material description

Three types of porous asphalt specimens are used in this study: PA4, PA8 and PA11, whose nominal maximum aggregate sizes are 4, 8 and 11 mm respectively. The mixtures for the PA8 and PA11 specimens are procured from a local mixing plant. They conform to Swiss standards and contain 6 mass-% polymer modified bitumen, PmB-E 45/80–65, and 0.2 mass-% cellulose fibers. The PA4 specimens are from a non-standard mixture fabricated using only the 2/4 mm fraction