Drying of Porous Asphalt Concrete Investigated by X-Ray Computed Tomography

I. Jerjen\textsuperscript{a,b,c}, L. D. Poulikakos\textsuperscript{a,*}, M. Plamondon\textsuperscript{a}, Ph. Schuetz\textsuperscript{a,d}, Th. Luethi\textsuperscript{a}, A. Flisch\textsuperscript{a}

\textsuperscript{a}Empa, Ueberlandstrasse 129, CH-8600 Dübendorf, Switzerland
\textsuperscript{b}ETH Zurich, Gloriastrasse 35, CH-8092 Zurich, Switzerland
\textsuperscript{c}Paul Scherrer Institute, CH-5232 Villigen, Switzerland
\textsuperscript{d}Lucerne University of Applied Sciences and Arts, Technikumstrasse 21, CH-6048 Horw, Switzerland

Abstract

Porous asphalt concrete is composed of aggregates, a bituminous binder and air voids which can form a complex network. Because rain water can easily drain through this network of voids, porous asphalt concrete is often used for improving the security of highways. However, porous asphalt concrete is often deteriorating fast due to its large contact area with environmental agents. A quantitative determination of the influence of rain water on the aging of porous asphalt concrete requires an understanding of water drainage and evaporation in the material. In this paper, the water evaporation rate in a sample of porous asphalt concrete was investigated by means of X-ray micro computed tomography. Discontinuities in the evaporation rate were observed. A qualitative inspection of the pore network allowed tentatively linking sudden acceleration of evaporation to the disappearance of water lids which were clogging pores.

© 2015 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Selection and peer-review under responsibility of Paul Scherrer Institut

Keywords: X-ray computed tomography; porous asphalt concrete; water evaporation; water lids

1. Introduction

Porous asphalt concrete (PA) is a special type of asphalt concrete with a porosity of up to 20%. In rain, the water does not stay on the road surface as it flows through the pores into the drainage system. Thereby, important safety

* Corresponding author. Tel.: +41-58-765-4479.
E-mail address: Lily.Poulikakos@empa.ch

1875-3892 © 2015 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).
Selection and peer-review under responsibility of Paul Scherrer Institut
doi:10.1016/j.phpro.2015.07.063
problems such as aquaplaning are avoided as well as low visibility due to splash and spray. In addition, due to its high porosity and surface texture, porous asphalt concrete is a low noise pavement reducing the initial noise emissions due to traffic in comparison to dense surfaces by as much as 4dBA (Angst et al., 2010). Due to its special function a significant surface area of the material comes in contact with water and air and therefore is prone to deteriorate faster than dense graded pavements. Water can cause the loss of adhesion between the binder and aggregates or the loss of cohesion within the binder, both resulting in the stripping phenomenon which further weakens the material. Therefore how the material reacts to water and the drying process are very relevant properties that need to be studied in detail. Depending on the particular situation the material can be completely submerged in water or stay wet after the drainage process. The later has been studied extensively using wind tunnel experiment considering drying through forced convection on the surface of the material (Poulikakos et al., 2013a) and drainage after submersion (Poulikakos et al., 2013b) and water uptake (Lal et al., 2014) using neutron radiography. The aim of the current study is to demonstrate the advantages of investigating drying of porous asphalt using X-ray computed tomography (CT): In addition to the global change of the water volume also local effects such as splitting and merging of water islands, as well as the opening and closure of water pathways can be studied.

2. Experimental setup

2.1. Sample preparation

From a 150 mm diameter laboratory compacted porous asphalt sample with maximum aggregate size of 8 mm (PA8) a cylinder with a diameter of about 30 mm and a height of about 67 mm was cut out. For the compaction, a gyratory compactor with 50 gyrations and a compaction temperature of 150°C was used. To have a representative volume element (RVE), the sample size should be 2.5 to 3 times larger than the maximum aggregate size but small enough to minimize the CT scan duration. The dry sample was put onto a hollow Plexiglas pedestal in a Plexiglas compartment as shown in Fig. 1. The compartment can be filled with water using a pipette. There are small holes in the pedestal which allow water from the compartment to enter the volume under the sample. When the water is removed by means of a syringe, the water stays in the volume under the asphalt, thus ensuring that the water in the asphalt cannot drain during the CT scans and water loss is due to evaporation through the samples top surface mainly. The space between the asphalt and the Plexiglas compartment at the top was sealed by plasticine: By this way, evaporation of the water to the side of the sample is reduced.

2.2. µCT measurement

The evolution in time of the three-dimensional distribution of water in an asphalt sample was obtained by means of an X-ray micro computed tomography setup at EMPA: First, a CT scan of the dry sample mounted in the Plexiglas compartment was taken, then the compartment was filled with water and another scan was executed. Then the water was removed from the compartment and 26 scans with a duration of 55 minutes were executed over a time period of 57 hours.

The components of the custom-made scientific X-ray instrument are an X-ray tube “XT9160-TXD” from Viscom, a high precision rotation table “UPR-160F air” mounted on three linear stages “LS-270” from Micos and an X-ray flat panel detector “XRD 1621 CN3 ES” from Perkin Elmer with a CsI scintillator. The X-ray tube was operated with an acceleration voltage of 160 kV and a current of 150 µA. A 1 mm thick Ti filter was mounted on the source to harden the X-ray spectrum. For each CT scan 720 radiographic images evenly distributed over 360° were recorded with 800 x 1000 pixels and a 3.6 s exposure time. The distances between the sample and the X-ray source and between the X-ray source and detector were 165.23 mm and 1017.34 mm, respectively. After beam-hardening and ring artefact corrections, the three-dimensional distribution of the absorption coefficient was
calculated by means of a Feldkamp algorithm (Feldkamp et al., 1984). The voxel size of the obtained three-dimensional image was 65 µm.

Fig. 2 shows a slice image of the 3D CT data of the wet asphalt sample just after drainage: The aggregates, bitumen, water and air are easily distinguishable. Cellulose fibers that were added to the mixture to reduce binder drain down due to high porosity of PA have similar grey values as water, though. It was verified that the sample location is stable during the whole measurement campaign, i.e. the change in the position was less than the size of a voxel. This allows for restricting the region of interest to the pores determined from the dry sample, and a straightforward segmentation of the water.

Fig. 1: (a) Scheme of sample holder: 1) is a Plexiglas compartment, 2) is the sample pedestal filled with water, 3) is massive Plexiglas. (b) Picture of asphalt sample mounted in a Plexiglas compartment (left) and X-ray source with Ti filter (right).

Fig. 2. Slice image of CT-scan of wet asphalt sample: The aggregates, bitumen, and water are easily distinguishable. Cellulose fibers have similar grey values as water.
2.3. 3D Image analysis

The reconstructed 3D CT data was analyzed using three different software tools: the open source program Fiji (Fiji, n.d.), the commercial software VGStudio MAX (VGStudio, n.d.) and the freeware GOM inspect (GOM, n.d.). Fiji was used to define the region of interest by creating a binary mask with value 0 outside of the sample and at the location of the stones and value 1 everywhere else (i.e. at the location of air, cellulose, water and bitumen). All CT datasets were multiplied by this mask before the data of the dry sample was subtracted from the data of the wet samples. By this procedure, new datasets were created which show exclusively the water distribution. These datasets were loaded into the VGStudio MAX software, filtered by a three-dimensional median filter of rank 1 and segmented by the surface determination function with automatic threshold (center of peaks in histogram). From the obtained surfaces STL(Surface Tesselation Language) files were created which were loaded into the GOM Inspect software for selecting connected water regions and determining their volumes at a given time.

3. Results

The X-ray µCT scans allow not only a four-dimensional visualization of the water distribution in the asphalt sample, but also precise volumetric measurements. Here, the reduction of the total water content due to evaporation is shown and mechanisms causing the observed discontinuities are investigated qualitatively.

The time evolution of the total water content in the sample and of the volume of a chosen water island is shown in Fig. 3. The sudden drops of the volume of the water island are due to splitting into two or more separate islands, as exemplary verified in Fig. 4.

![Fig. 3: The graph shows the change in the water volume due to evaporation of the whole sample (filled, right scale) and one water island (open, left scale).](image)

Sudden drops of the total water content require another explanation, though. At constant environmental conditions, the evaporation rate is proportional to the water-air surface area. Therefore, if the water in a pore evaporates to a point where the pore diameter suddenly increases, the evaporation rate may increase. A closer look at the locations of the water loss after 12 hours reveals that the drop in the water volume is mainly due to accelerated loss at two sites, as indicated in Fig. 5. The examination of the sites indicates at another mechanism leading to a sudden acceleration of the evaporation: It seems that a water lid blocks the pore heading to the outside of the sample and that the evaporation of the inner water volume accelerates after the disappearance of the lid. The water lid would function in analogy to the volatile lids proposed for preventing the evaporation of solvent in chip-based nanovials (Litborn and Roeraade, 2000).
Fig. 4: Pores network of asphalt sample (transparent green), (a) a chosen water island (red) after 3.6 hours and (b) its separation in two parts (blue and red) after 5.58 hours.

Fig. 5: Asphalt pores filled with air (transparent green) and with water at time 11.41 (red) and 15.27 hours (blue). (a) Site of sudden water loss 1, (b) site of sudden water loss 2. The arrows indicate the location of the water lid.

4. Conclusion

X-ray μCT imaging allows observing the evolution of the water content in asphalt over time, at least for small samples. Since it is a three-dimensional measurement, root causes for discontinuities in the evaporation rate can be investigated. Indications were found that the evaporation depends not only on global proprieties like mean pore volume and diameter but also on the detailed structure of the pore network. In particular, blocking water lids formed by surface tensions at the outer boundary of the sample appear to have a strong influence on the
evaporation rate. Actually, similar phenomena were studied in silicon microstructures (Litborn and Roeraade, 2000). However, a simulation of the evaporation of water in porous asphalt taking into account the exact geometry is required to understand all the mechanisms determining the evaporation rate.

References

Angst, C., Beltzung, F., Bosshardt, D., Ziegler, T., Bühlmann, E., 2010. Lärmarme Strassenbeläge innerorts Jahresbericht 2010.
Feldkamp, L.A., Davis, L.C., Kress, J.W., 1984. Practical cone-beam algorithm. J. Opt. Soc. Am. A 1, 612–619.
Fiji, n.d. Fiji [WWW Document]. URL http://fiji.sc/Fiji
GOM, n.d. GOM Inspect [WWW Document]. URL http://www.gom.com/de/3d-software/gom-inspect.html
Lal, S., Poulikakos, L.D., Sedighi Gilani, M., Jerjen, I., Vontobel, P., Partl, M.N., Carmeliet, J.C., Derome, D., 2014. Investigation of Water Uptake in Porous Asphalt Concrete Using Neutron Radiography. Transp. Porous Media 105, 431–450
Litborn, E., Roeraade, J., 2000. Liquid lid for biochemical reactions in chip-based nanovials. J. Chromatogr. B Biomed. Sci. Appl. 745, 137–147
Poulikakos, L.D., Saneinejad, S., Gilani, M.S., Jerjen, I., Lehmann, E., Derome, D., 2013a. Forced Convective Drying of Wet Porous Asphalt Imaged with Neutron Radiography. Adv. Eng. Mater. 15, 1136–1145
Poulikakos, L.D., Sedighi Gilani, M., Derome, D., Jerjen, I., Vontobel, P., 2013b. Time resolved analysis of water drainage in porous asphalt concrete using neutron radiography. Appl. Radiat. Isot. 77, 5–13
VGStudio, n.d. VGStudio MAX [WWW Document]. URL http://www.volumegraphics.com/products/vgstudio-max/basic-functionality/