Investigations on microstructure characteristics of porous pavement based on X-ray CT scanning

Tom Törzs\textsuperscript{i)}, Jürgen Grabe\textsuperscript{ii)}, Guoyang Lu\textsuperscript{iii)}, Markus Oeser\textsuperscript{iv)}

\textsuperscript{i)} PhD student, Institute of Geotechnical Engineering and Construction Management, Hamburg University of Technology (TUHH), Harburger Schlossstrasse 20, 21079 Hamburg, Germany.
\textsuperscript{ii)} Professor, Institute of Geotechnical Engineering and Construction Management, Hamburg University of Technology (TUHH), Harburger Schlossstrasse 20, 21079 Hamburg, Germany.
\textsuperscript{iii)} PhD student, Institute of Highway Engineering, RWTH Aachen University, Mies-van-der-Rohe-Straße 1, 52074 Aachen, Germany.
\textsuperscript{iv)} Professor, Institute of Highway Engineering, RWTH Aachen University, Mies-van-der-Rohe-Straße 1, 52074 Aachen, Germany.

ABSTRACT

Gathering insights on materials at pore scale using digital imaging techniques, such as X-ray computed tomography (CT), gains more and more attention in various fields of engineering disciplines. The better understanding of material properties, internal structures, and material behaviour has generated many scientific and industrial advances.

Investigations on porous materials, especially the visualisation of the pore space, allow the derivation of macroscopic material properties and provide a basis for numerical calculations, e. g. flow or contaminant transport through three-dimensional pore structures. The investigated porous material in this study is used in water-permeable road constructions as a novel pavement material aiming at instant drainage of rainfall into the subgrade and subsoil. Commonly used porous asphalt is made utilising bitumen-based binder materials. In this case, however, an innovative binder material based on polyurethane (PU) is used to form a flexible and porous pavement layer. The utilisation of this binder material not only increases the functionalities of the pavement layer but also increases rutting resistance and fatigue behaviour. This paper gives insights on the pore space obtained from CT-scans of two different pavement compositions of novel porous pavement material. The compositions vary in terms of particle size distribution of the utilised grains and the maximum grain diameter. The segmentation process of the obtained CT-images into the components of the multiphase media, i. e. grains, pore space, and binder material, as well as the reproduction of the three-dimensional models will be presented. Also results of investigations on the representative elementary volume for two volume-dependent properties will be demonstrated.

Keywords: pavement material, porous asphalt, image analysis, X-ray CT, representative elementary volume

1 INTRODUCTION

The content of this study was collated in the course of a collaborative research project at the RWTH Aachen University and Hamburg University of Technology (TUHH). The project focus lies on hydraulic mechanical interactions in water-permeable pavements under consideration of unsaturated states.

The material investigated in this study is a porous medium as used in highway engineering: a novel composition of porous pavement material utilising an alternative binder material. Commonly used binder materials are bitumen based. The permeable pavement mixtures, examined in this study, are composed with polyurethane as a substitute to the commonly used bitumen binder. Polyurethane is a multifunctional material, which in addition is widely used in many different fields, e. g. building and construction materials, furniture, textiles, or electronics. The successful substitution of the binder material in porous asphalts and its application has been shown in several studies (Renken and Oeser 2015; Renken, Kreischer, and Oeser 2015; Wang et al. 2017; Törzs et al. 2018). Porous pavement surface layers are utilised in areas where it is intended to recycle occurring rainfall to the subsoil and prevent surface sealing in municipal areas. The natural groundwater cycle might be highly irritated in urban areas resulting in micro climatic changes. In general, porous asphalt comes with advantages such as high skid resistance, low noise, and less splash and spray as well as a reduction of reflected lights. Porous asphalt pavement can significantly improve driving quality in wet weather conditions (Nicholls 1997; Liu and Cao 2009).

Part of the research project focuses on the visualisation of internal structures of polyurethane-bound pavement materials allowing a review on the bounding effect of the utilised binder material. Digital imaging techniques, such as X-ray computed tomography, are generally used in biological and medical applications. Other usages cover scientific
applications, such as material sciences and oil and gas sciences, as well as engineering applications in general. The use of CT-scanning offers the opportunity to acquire high quality images of the internal structures of porous media for further digital reconstruction and investigations.

2 MATERIALS

In this study, two compositions of polyurethane-bound porous pavement materials are investigated, see Fig 1. The investigated compositions differ in terms of particle size distribution of the aggregates and maximum grain diameters. The aggregates are a fine diabase gravel and a limestone filler. The two compositions, mixture A and mixture B, have maximum grain diameters of 8 mm and 5 mm, respectively. The corresponding particle size distributions are given in Fig. 2.

![Fig. 1. The specimens of PU-bound pavement materials of type A (left) and B (right). Diameter $d = 50$ mm and height $h = 40$ mm.](image1)

![Fig. 2. Particle size distributions of the aggregates used in the preparation of the specimens of PU-bound pavement compositions.](image2)

It was intended to keep the binder (PU) content constant for both compositions. Polyurethane consists of various polymers that can be made by the polyaddition reaction of a diisocyanate with a polyol. The synthesis is based on the connection of isocyanates and hydroxyl groups that lead to the creation of a urethane group (Prisacariu 2011).

The specimens are prepared in a cold mixing process in which the aggregates and both components of the PU are brought together. The PU reaction immediately begins and after a working time of approximately 15 min a flexible porous medium is created. The specimen preparation follows the descriptions in Wang et al. 2017. The cylindrical specimens used for this study were received from drilling cores with a diameter of 50 mm from a larger plate. This plate was created in a frame after the mixing process. After drilling, the cores were cut to a height of 40 mm. In the course of the research project, mechanical and hydraulic properties were determined in numerous laboratory experiments. Selected mechanical, geotechnical, and hydraulic parameters are presented in Table 1.

| Property                  | Unit   | Type A     | Type B     |
|---------------------------|--------|------------|------------|
| Compressive strength      | MPa    | 18.63 ± 1.39 | 16.98 ± 0.90 |
| Tensile strength          | MPa    | 3.36 ± 0.38  | 2.18 ± 0.29  |
| Young’s modulus $E$       | GPa    | 6.64 ± 0.08  | 3.31 ± 0.29  |
| Poisson’s ratio $\nu$     |        | 0.210 ± 0.032 | 0.164 ± 0.024 |
| Shear modulus $G$         | GPa    | 2.75 ± 0.08  | 1.42 ± 0.15  |
| Bulk density $\rho_{\text{bulk}}$ of the mixture | g/cm$^3$ | 1.865 | 1.927 |
| Porosity $n$              |        | 0.286 | 0.259 |
| Coefficient of permeability $k$ | m/s   | $8.4 \cdot 10^{-3}$ | $7.9 \cdot 10^{-3}$ |

3 METHODS

The workflow of this study including utilised software for the investigations on the aforementioned specimens are described in this section. Two different compositions of PU-bound pavement material were studied in a CT-scanning system. The CT-scanning system utilised is located at the Laboratoire 3SR in Grenoble (Viggiani et al. 2015; Milatz and Grabe 2019). In order to obtain images of the internal structures, the specimens were scanned in the CT system with a given scanning peak kilovoltage of 120 kVp and a scanning current of 250 $\mu$A. Further scan parameters are summarised in Table 2. Each of the two specimens was scanned a total of 4 times for averaging image data, whereby an isotropic voxel edge length of 30 $\mu$m was maintained. The obtained image data was used for threshold-based segmentation of the material's phases, i.e. void space, PU-binder, and aggregates. From here three-dimensional models were rebuilt from the separated phases.

| Table 2. Properties of the utilised CT-scanning system. |
|-----------------------------------------------------------|
| X-ray tube voltage | 120 kVp |
| X-ray tube current | 250 $\mu$A |
| Projections/360° revolution | 1200 |
| Isotropic voxel size | 30 $\mu$m |
| Acquisition time | Approx. 3.5 h |
| Acquisition mode | Helicoidally |
The scanning procedure results in stacks of TIFF-images whereby each image represents one slice of the scanned specimen. The slices were cropped using Fiji (Schindelin et al. 2012). Image data treatment and the segmentation process were done in Avizo 9.7.0 (Avizo User’s Guide 2018). First, greyscale normalisation was conducted on the images to increase image contrast for better phase segmentation. Subsequently, the images were filtered using 3D median and 2D non-local means filters (Gastal and Oliveira 2012) for image noise reduction. Phase segmentation was done by simple thresholding, which was possible due to evident peaks in the greyscale histograms. Exporting the segmented images of the individual slices to MATLAB (The MathWorks, Inc. 2018) allows further investigations on the representative elementary volume (REV). A REV is the smallest volume whose properties are representative for the whole medium (Bear 2013; Costanza-Robinson, Estabrook, and Fouhey 2011).

For this purpose, cubic volumes $V$ with a maximum edge length $L$ fitted into the cylindrical volume of the scanned drilling core were exported from the scans of both specimens. The exported data contains labelled data of the segmented phases in the volume, i.e. a three-dimensional tensor in which every entry represents one voxel. Each voxels’ content is indicated by a scalar: 1 = void, 2 = PU, 3 = aggregates. MATLAB was used to further investigate the labelled datasets to find representative elementary volumes for two properties: porosity $n$ and PU-binder content $c$. Therefore, a cubic partial volume $V^*$ is expanded stepwise starting from the centre voxel inside the volume $V$. For each step in the expansion the unitless and volume-dependent properties, namely porosity $n$ and PU-binder content $c$, are calculated using equations 1 and 2.

$$n = \frac{\nu_{\text{void}}}{V^*} = \frac{\nu_{\text{void}}}{\nu_{\text{void}} + \nu_{\text{PU}} + \nu_{\text{aggregates}}}$$

$$c = \frac{m_{\text{PU}}}{m_{\text{PU}} + m_{\text{aggregates}}}$$

with $V_{\text{void}}$, $V_{\text{PU}}$, $V_{\text{aggregates}}$ corresponding to the phase volumes inside the partial volume $V^*$. The superscript “*” indicates that the calculated volumes are partial volumes of the partial volume $V^*$. $V^*$ is also equal to the sum of all phases in the observed volume, i.e. $V^* = \nu_{\text{void}} + \nu_{\text{PU}} + \nu_{\text{aggregates}}$.

The PU-binder content $c$ is a value in a unit of weight by weight and therefore the geometrical data, i.e. the partial volumes $V_{\text{PU}}$ and $V_{\text{aggregates}}$, needs to be converted into weights. This is obtained by multiplying the corresponding volumes with the materials’ densities. The PU-binders’ density is $\rho_{\text{bulk,PU}} = 1.09 \text{ g/cm}^3$ and the aggregates’ mean density is $\rho_{\text{bulk,aggregates}} = 2.85 \text{ g/cm}^3$.

### 4 RESULTS

After image cropping, the normalisation of the greyscale images for contrast enhancements was performed. In general, a greyscale histogram shows the distribution of levels of grey in a greyscale image. The greyscale histogram is a statistical graph with levels of grey on the x-axis and the count of voxels for each grey level on the y-axis. Digital 3D-images are composed of voxels (vx). The number of bits used to represent these voxels determines the number of grey levels available to describe each voxel. For this study, a 16-bit representation of the images was applied. This provides $2^{16} - 1 = 65,535$ levels of grey for the representation of each voxel. A normalisation stretches the data to the full range resulting in a contrast enhancement. A higher contrast is aimed for further image segmentation as the threshold ranges are enlarged. Raw and normalised histograms are given in Fig. 3 for both porous asphalt compositions A and B. For both, raw and normalised graphs, the first peaks in the histogram correspond to the void space, the second plateau-like peaks correspond to the PU-binder material, and the third peaks correspond to the aggregates.

![Fig. 3. Raw and normalised greyscale value histograms for porous asphalt compositions A and B.](image)

After the greyscale histogram normalisation, the images were smoothed by applying filters to improve their quality for the following segmentation process. A median filter was followed by a non-local means filter (Avizo User’s Guide 2018). Segmentation means assigning labels to image voxels that identify and separate objects in a 3D image. The images were segmented using a simple thresholding technique. Firstly, the phase of aggregates was separated using a threshold and adding a separate objects module to the output. Segmented particles might be visualised as a connected volume due to the resolution of the obtained images. The void space was segmented by applying thresholds to the filtered data. After the segmentation of the aggregates and the void space the phase of PU-binder...
can easily be obtained by subtracting the already obtained label fields (aggregates and void space) from the whole volume. The working procedure from the raw image data towards segmented label fields for both specimens is illustrated in Fig 4 in detailed cut sections with an edge length of 335 px.

![Fig. 4. Working procedure from the raw image data towards labelled image data for mixture A and B: (a) raw image data, (b) greyscale histogram normalisation, (c) median filter, (d) non-local means filter, (e) label fields: white – air, dark grey – PU, light grey – aggregates. Details with an edge length of 335 px from the centres of the specimens in the vertical direction are shown.](image)

The study on the REV was conducted to find a volume’s minimum edge length $L$ that allows the derivation of a property dependent on the volume itself. A property derived from a volume with this edge length is representative for the whole porous medium and can be used for further investigations. Following the procedure described in section 3, the properties porosity $n$ and PU-binder content $c$ varying dependent on edge length $L$ are illustrated in Fig 5 for both compositions. REVs can be found for both specimens and for both properties. After the graphs are reaching plateau-like conditions and the investigated properties are not changing with increasing edge lengths, the edge length $L$ can be determined by subjective evaluation. It is apparent that the property of porosity $n$ reaches a stable condition after an increasing edge length of 800 px for both mixtures. PU content $c$ shows no significant changes after 600 px for both mixtures.

The labelled volumes with edge lengths of 800 px and 600 px can be considered to determine the porosity $n$ and PU content $c$, respectively. Results of those two properties for both compositions A and B are given in Table 3.

Further, Avizo is capable of calculating the aggregate’s volumes $V_{\text{grain}}$. Equation 3 allows the calculation of diameters equivalent to spherical grains for the labelled aggregates inside the volume $V$. Volumes with an edge length of 800 px were investigated, see Fig. 7 (c).

$$\text{eq. } \phi = \frac{3}{\sqrt{\pi}} \frac{V_{\text{grain}}}{\pi}$$

From a list of equivalent diameters, it is now possible to reconstruct equivalent particle size distributions of the aggregates of both compositions and compare the output to the laboratory determined distributions. The results are depicted in Fig. 6 and Table 4.

![Fig. 5. Three-dimensional study on the representative element volume on porosity $n$ (-) and polyurethane content $c$ (g/g) on pavement compositions A and B.](image)

| Table 3. Porosities $n$ and PU-binder content $c$ determined from the REVs. |
|---|---|---|
|   | Mixture A | Mixture B |
| Edge length $L$ (px) | 800 | 800 |
| Porosity $n$ (-) | 0.214 | 0.228 |
| Edge length $L$ (px) | 600 | 600 |
| PU-content $c$ (g/g) | 0.091 | 0.114 |
Fig. 6. Particle size distributions of the investigated specimens of PU-bound pavement materials. Laboratory determined data and reconstructed equivalent particle size distributions are shown.

Table 4. Differences Δ(%) in the particle size distributions of the granular aggregates determined in the laboratory and derived from reconstructed volumes.

| Corresponding particle diameter (mm) | Δ(%) Mixture A | Δ(%) Mixture B |
|-------------------------------------|---------------|---------------|
| 0.063                               | 0.00          | 0.00          |
| 0.125                               | 5.15          | 21.45         |
| 0.250                               | 39.60         | 27.91         |
| 0.500                               | 34.00         | 21.69         |
| 1.000                               | 34.27         | 19.29         |
| 2.000                               | 30.59         | 10.29         |
| 4.000                               | 16.91         | 0.76          |
| 8.000                               | 3.89          | 1.18          |
| 16.000                              | 0.67          | -             |

Three-dimensional models were reconstructed from the segmented label fields and are depicted in Fig 7. The network of pores is given on the left, the PU-binder is shown in the middle, and the aggregates on the right.

Fig. 7. Segmented and separated phases of mixture A (top) and mixture B (bottom). From left to right: (a) void, (b) polyurethane binder, and (c) aggregates. Edge length is 800 px in all of the volumes.

5 CONCLUSIONS

The obtained images and reconstructed volumes presented in this paper deliver insights on the bounding effect of polyurethane binder which is used as a substitute for commonly used bituminous binders in road construction’s paving layers. Digital imaging techniques have a huge potential in terms of visualisation and analyses of porous asphalt. They allow the determination of the covering thickness of the binder materials. The quality of the mixing procedure from real pavements can easily be determined from drilling cores. Also, heterogeneities or imperfections could easily be located. It was shown that the utilised CT-scanner was suitable to
obtain images in a high quality for further analysis. Representative element volumes for the properties, porosity and PU-binder content, were found to be located at edge length of 800 px and 600 px, respectively, which is equal to 24 mm and 18 mm. Calculated porosities differ slightly from the production target values. PU-binder contents are in a reasonable range.

Differences in the reconstructed equivalent particle size distribution compared to the laboratory determined particle size distribution had a maximum of 39.6 % for mixture A and 27.91 % for mixture B. These differences might be explained by the amounts of particles with a diameter in the same length as the resolution of 0.03 mm which might not be recognised in the segmentation procedure. More decisive, however, is the fact that the reconstructed particle size distributions are obtained from spherical particles with equivalent volumes. These geometrical differences might be accountable for the presented deviations.

The obtained reconstructed volumes are to be seen as a pre-step for further numerical analyses planned in the course of the research project. The volumes can easily be meshed and exported to common finite element solvers. For future research, it is planned to investigate the effect of different clogging stages on hydraulic properties, such as hydraulic conductivity in saturated in unsaturated states. Also, more detailed investigations on inaccessible pores in the structures and micro pores in the PU-binder are in the scope of future investigations.

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REFERENCES

1) Avizo User’s Guide. 2018. ‘Thermo Scientific® Avizo® Software 9.7.0 - User’s Guide’. Berlin. url: https://www.fei.com/software/amira-avizo/.
2) Bear, J. Dynamics of fluids in porous media. Courier Corporation, 2013.
3) Costanza-Robinson, M. S., Benjamin D. Estabrook, and D. F. Fouhey. 2011. ‘Representative Elementary Volume Estimation for Porosity, Moisture Saturation, and Air-Water Interfacial Areas in Unsaturated Porous Media - Data Quality Implications’. Water Resources Research 47 (7): 44. doi: 10.1029/2010WR009655.
4) Gastal, E. S. L., and M. M. Oliveira. 2012. ‘Adaptive Manifolds for Real-Time High-Dimensional Filtering’. ACM Trans. Graph. 31 (4). doi: 10.1145/2185520.2185529.
5) Liu, Q., and D. Cao. 2009. ‘Research on Material Composition and Performance of Porous Asphalt Pavement’. Journal of Materials in Civil Engineering 21 (4): 135–40. doi: 10.1061/(ASCE)0899-1561(2009)21:4(135).
6) MathWorks, Inc. 2018. ‘MATLAB® Primer’. url: https://mathworks.com/.
7) Milatz, M., and J. Grabe. 2019. ‘Microscopic Investigations of the Hydro-Mechanical Behaviour of Unsaturated Granular Media with X-Ray CT’. In Proc. of the 7th Asia-Pacific Conference on Unsaturated Soils. Nagoya, Japan. (accepted for publication)
8) Nicholls, J.C. 1997. Review of UK Porous Asphalt Trials. Report (Transport Research Laboratory (Great Britain)). Transport Research Laboratory.
9) Prisacaru, Cristina. 2011. Polyurethane Elastomers - From Morphology to Mechanical Aspects. Berlin Heidelberg: Springer Science & Business Media.
10) Renken, L., S. Kreischer, and M. Oeser. 2015. ‘Entwicklung von Deckschichtmaterialien Für Versickerungsfähige Verkehrsflächenbefestigungen Auf Basis Alternativer Bindemittel - Teil II: Anspreche Der Performance’. Straße Und Autobahn 11: 776–84.
11) Renken, L., and M. Oeser. 2015. ‘Entwicklung von Deckschichtmaterialien Für Versickerungsfähige Verkehrsflächenbefestigungen Auf Basis Alternativer Bindemittel - Teil I: Festigkeit, Permeabilität, Kornverlust’. Straße Und Autobahn 9: 601–8.
12) Schindelin, J., I. Arganda-Carreras, E. Frise, V. Kaynig, M. Longair, T. Pietzsch, S. Preibisch, et al. 2012. ‘Fiji: An Open-Source Platform for Biological-Image Analysis’. Nature Methods 9 (June): 676. doi: 10.1038/nmeth.1929.
13) Törzs, T., J. Grabe, G. Lu, and Oeser. 2018. ‘Investigations on the Water-Retention Behaviour of Water-Permeable Pavement Materials Based on Innovative Binder Materials’. In Proc. of 7th International Conference on Unsaturated Soils UNSAT2018, Hongkong, China.
14) Viggiani, G., E. Andò, D. Takano, and J. Santamarina. 2015. ‘Laboratory X-Ray Tomography: A Valuable Experimental Tool for Revealing Processes in Soils’. doi: 10.1520/GTJ20140060.
15) Wang, D., A. Schacht, Z. Leng, C. Leng, J. Kollmann, and M. Oeser. 2017. ‘Effects of Material Composition on Mechanical and Acoustic Performance of Poroelastic Road Surface (PERS)’. Constr. Build. Mater. 135: 352–60. doi: 10.1016/j.conbuildmat.2016.12.207.