Investigations on the water-retention behaviour of water-permeable pavement materials based on innovative binder materials

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ABSTRACT: In general, the determination of soil hydraulic parameters given by drainage and imbibition paths in the water-retention curve is of major interest to predict hydraulic and mechanical responses of porous media. This study focuses on the estimation of drainage and imbibition paths of different water-permeable pavement materials based on an alternative binder material. Conducted studies regarding fatigue and deformation resistance proved the positive application of polyurethane as an alternative to commonly used binders. However, this study focuses on the hydraulic properties, i. e. the water-retention behaviour, of polyurethane-bound pavement materials. A total of three different material compositions is investigated in this study. The applied method to determine the water-retention curve in the low suction range in the soil-mechanics laboratory is presented herein. All of the materials show low air entry values on the drainage paths. Further, on re-wetting even lower pressures are obtained. A correlation between particle size distribution and air entrapment becomes evident. In conclusion, the highly permeable materials show relatively low capillary effects whose influence on the design and construction of water permeable roads still has to be characterised.

1 INTRODUCTION

With increasing trends in land sealing in municipal areas the usage of water-permeable structures seems to be a logical reaction to restore the natural groundwater and support the natural ecosystem. Land sealing is caused by increasing advances in urban and infrastructural development. In addition, land sealing leads to a noticeable decrease of the natural groundwater recharge and has an effect on the local climatic conditions. An opportunity to counter these effects might be the application of innovative permeable road structures whereby a return of occurring rainfall to the natural ecosystem can be generated. Further, replacing bituminous binder materials, which are usually made from crude oils and used in regular water-permeable asphalt compositions, with an alternative resource-conserving material seems promising. Aziz et al. (2015) give an overview on alternative binder materials for regular pavements concluding that the use of bio-based and waste materials could be a reasonable alternative to bitumen-based pavements. Water-permeable pavements are used as a surface layer for water-permeable road structures to facilitate instantaneous infiltration of water into the underlying base courses down to the subsoil. Several studies have shown that using polyurethane (PU) as an alternative binder material can create an open porous surface layer with a high fatigue and deformation resistance against traffic loads, whereby on the other hand providing excellent permeabilities and infiltration rates for instantaneous drainage of water into the underlying structure (Renken and Oeser 2015, Renken et al. 2015, Renken et al. 2015, Wang et al. 2017). Polyurethanes are produced from the chemical polyaddition of the two components polyol and isocyanate. They can be synthetic resins or structural foams and are generally utilised in a wide range of fields, e. g. building and construction materials, electronics, furniture, and textiles. Petrochemical resources are limited and thus effort is done in finding alternatives in renewable resources. The polyol component of polyurethane can be produced from resources, such as bio-based oils, resulting in an environmental sustainable product (Evertz 2009, Ionescu 2016).

In comparison to areas covered by grass or plants, water-permeable road structures show no biotic soil zone operating as a natural filter to dissolve pollutants in the seepage water. If, however, due to local circumstances the application of water-permeable road constructions is needed to recycle rainwater, soil and water conservation should be taken into account.

Passing of vehicles can affect the pore air and pore water pressures and thus influence the capillary pressure within the pavement and subsoil (Grabe and Milatz 2014). The capillary pressure is related to the degree of saturation and can be expressed as water-retention curve, which plays a major role in understanding the behaviour of unsaturated soils. In this study results from experimental investigations on the water-retention behaviour of water-permeable PU-bound pavement materials is presented. The conducted experiments focus on the main drainage path and on the subsequent main imbibition path of the water-retention curve.

2 MATERIALS AND METHODS

2.1 *Materials*

The water-retention behaviour of three compositions (mixtures) of PU-bound pavement is investigated. The material in its unbound form is a (medium to coarse) sandy fine gravel consisting of diabase. Mixtures A and B are prepared with a filler, whereby powdered limestone has been used. Diabase and powdered limestone are widely used in regular bituminous porous asphalt mixtures (FGSV 2013). The corresponding particle size distributions of the unbound material for the different mixtures are given in figure 1. Herein, the difference in mixture A and B becomes evident: mixture A consists of three grain fractions, i. e. 0/2 mm, 2/5 mm, and 5/8 mm, and mixture B consists of two grain fractions, i. e. 0/2 mm, 2/5 mm. Thus, the maximum grain diameters of mixture A and B are 8 mm and 5 mm, respectively. Mixture C is prepared from two grain fractions, i. e. 0/2 mm and 2/5 mm but without the application of a filler. Information on the amounts of the aggregates and PU-binder as well as related porosities, relative densities and coefficients of permeability of the mixtures can be taken from table 1. The relative densities and the particle size distributions correspond to the coefficients of permeability of the investigated mixtures.

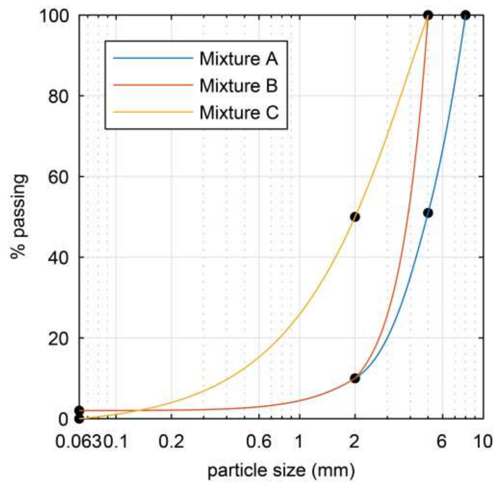

Figure 1. Particle size distributions of the investigated mixtures.

The v|tome|x Industrial High-Resolution CT & X-Ray System manufactured by Phoenix was employed to carry out the tests. The specimens were measured in the μCT system with a given scanning voltage of 190 kV and scanning current of 300 μA in order to obtain images of the internal structure of the investigated pavement mixtures. Image processing was performed by the image analysis software VGStudio Max by Volume Graphics GmbH. Three dimensional data was collected on mineral and porosity distribution to estimate the porosity.

The specimens for the scans were prepared in the same way as the specimens on which the investigations on the retention behaviour have been conducted. The specimens used to determine the porosities have a cylindrical shape with a diameter of 80 mm and a height of 40 mm, while the specimens used for the tests on the retention behaviour have a diameter of 50 mm and a height of 10 mm. All of the specimens are drilling cores, which were extracted from a plate and cut into the specific height. Top views on the drilling cores used to determine the water-retention behaviour are given in figure 2. To minimise boundary effects from the top or bottom of the drilling cores caused by clogging of the boundary pores by PU, only inner specimen were tested in this study.

Figure 2. Top view on specimens of drilling cores with a diameter of 50 mm. Mixture A (left), mixture B (middle), mixture C (right).

When producing the mixtures from aggregates and PU in the given mass fractions presented in table 1, the yet fluent PU is brought together with the aggregates covering every single grain with a thin PU-coating. After hardening of the PU, the coated grains are bound together in the contact points establishing a stable and highly permeable 3D-structure.

The specimens' saturated hydraulic conductivities (permeabilities) were determined by vertical permeability tests in the laboratory of RWTH Aachen University. Therefore, the water flow through the specimen was quantified in a defined time at a constant hydrostatic head, following the instructions presented in FGSV (2009). The mean coefficients of permeability for the different specimens are also presented in table 1. They are in good agreement with the requirements for water-permeable road constructions, as presented in FGSV (2013), wherein a coefficient of permeability $k_s \geq 5.4 \times 10^{-5}$ m/s is required.

As presented in in Renken et al. (2015) and Törzs et al. (2018) the suction range in which the pavement material will drain is very low, i. e. less than 1 kPa. Thus, a method has to be chosen which is capable of controlling suction steps with a very high resolution and in a relatively low range.

Table 1. Basic properties of the three investigated mixtures.

parameter (unit)	mixture A	mixture B	mixture C
mass fraction (-)			
aggregates	0.94	0.94	0.94
thereof filler	0.02	0.02	none
PU-binder	0.06	0.06	0.06
bulk density ρ_b (g/cm³)			
aggregates	2.85	2.85	2.85
filler	2.80	2.80	none
PU-binder	1.09	1.09	1.09
porosity n (-)			
mixtures	0.283	0.289	0.183
relative density ρ_d (g/cm³)			
mixtures	1.86	1.84	2.12
coeff. of permeability k_s (10^{-3} m/s)			
mixtures	8.4	7.9	3.8

2.2 *Test setup and procedure*

Due to the very low suction range, in which the investigations are carried out, the experiments on the water-retention behaviour of specimens of the three mixtures A, B, and C were conducted using the method of the hanging water column, as proposed in ASTM D6836-16. The setup used in this study slightly varies from the setup proposed in the standard, but the testing principle remains the same. Instead of using the proposed funnel to hold the soil specimen a specimen base pedestal is used, which has been successfully used in numerous tests on the water-retention behaviour of sands by Törzs (2015) and Milatz et al. (2016). Additionally, the same pedestal was used to investigate similar pavement materials inside a pressure plate apparatus (Renken et al. 2015).

Further, a burette with a scale is attached to the pedestal to measure the water outflow due to suction steps applied by a vacuum system. The suction supply system is implemented using two water reservoirs at different elevations resulting in an accurate tool to control the applied vacuum. The applied vacuum can be read from the air pressure transducer (Kyowa PGM-02KG), which is directly implemented in the system. The degree of saturation S_r can be quantified by correlating the amount of water flowing in or out of the specimen, which can be read from the burette connected to the specimen base pedestal, with the porosity. The burette is arranged horizontally, whereby the elevation should be the same as the bottom of the specimen, so the applied vacuum is theoretically equal to the suction inside the specimen. The applied test setup is depicted in figure 3 and also described in Törzs et al. (2018).

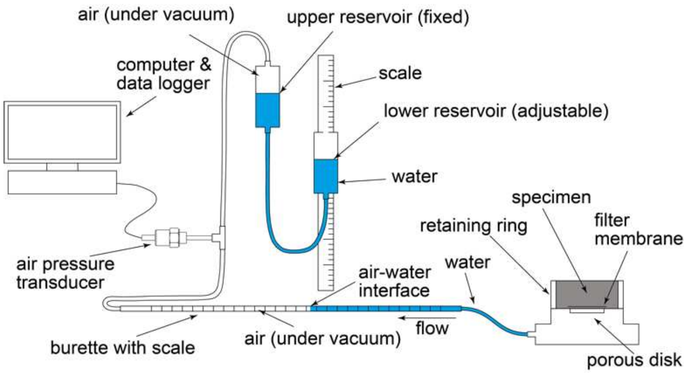

Figure 3. Modified hanging water column apparatus following ASTM D6836-16

In the beginning of a test series a specimen of the pavement material needs to be saturated with water. To obtain full saturation of the accessible pores the specimen is put in deionised and deaerated water. Further, the specimen undergoes several hours in a vacuum chamber to fully deaerate the pores. The same deaeration process will be applied for the specimen base pedestal, the porous disk, and the filter membrane. The specimen base pedestal is equipped with small channels to hydraulically connect the specimen and the burette. The porous disk has a high permeability and ensures a distributed drainage and imbibition over the specimen's cross section. The microporous filter membrane with a pore diameter of 0.8 µm (Pall Corp.) has a high air entry value and thus ensures that drainage and imbibition boundary conditions only affect the water phase inside the specimen. After the deaeration process of the components and the specimen, the specimen is encapsulated by a latex membrane, which is fixed by o-rings. The specimen base pedestal, as well as the porous disk, and the microporous membrane are screwed together maintaining submerged conditions to avoid air to enter the pores of the specimen or the channels of the base pedestal. The specimen is fixed on top of the pedestal with O-rings and afterwards taken out of the water resulting in a fully saturated system that now can be attached to the burette. A fully saturated specimen of mixture A installed on the specimen base pedestal is presented in figure 4.

After waiting for the water-air interface in the burette and the water-air interface in the specimen to come to equilibrium, the experiment is ready to be conducted. Throughout the whole experiment, the specimen is covered by a cling film perforated with small holes to minimise evaporation from the specimen but on the other hand ensuring hydraulic contact to the atmosphere. In the beginning of the experiment, the adjustable reservoir is lowered until a specific negative air pressure (vacuum) is reached. The applied vacuum can be directly read from the computer and adjusted as needed. Induced by the applied vacuum, the specimen begins to drain into the burette. After reaching equilibrium, i. e. no water movements are identifiable in the burette, the amount of drained water is quantified by reading the value from the scale on the burette. This procedure is repeated for every suction step to obtain the main drainage curves for every mixture. After reaching a specific suction, the load direction is changed and the water reservoir is raised incrementally to obtain the imbibition curves of the materials.

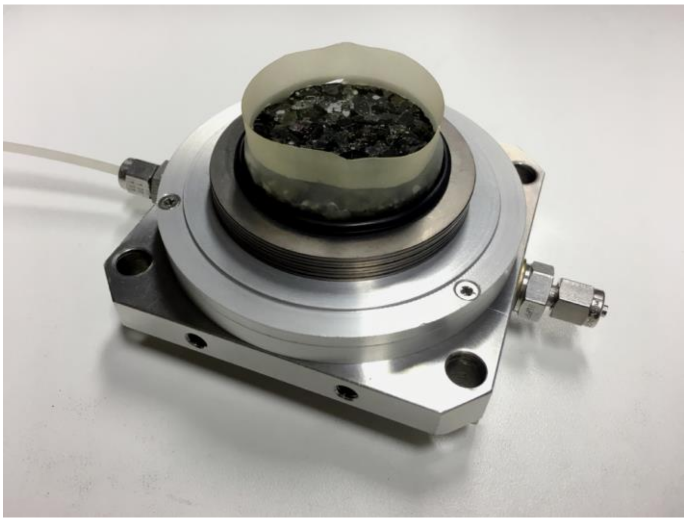

Figure4. Assembled specimen base pedestal equipped with a fully saturated specimen made of mixture A.

3 TEST RESULTS

In this section selected test results of experiments on the water-retention behaviour of the three characterised PU-bound pavement mixtures will be presented and discussed. Further, the obtained data is fit to the empirical model by van Genuchten (1980), which was originally developed to describe the water-retention behaviour of soils and has been widely used in geotechnical and environmental applications.

3.1 *Imbibition and drainage behaviour*

Results of the conducted tests on the drainage behaviour of the three mixtures of PU-bound pavement material are depicted in figure 5. The saturation is given in terms of actual saturation S_r, as given by equation 2. Besides the raw data from the experiments, parameter optimized curves given by equation 1 are added. As described above, the conducted drainage experiments started from fully saturated states. The materials show different air entry values, whereby the observation can be made that the air entry value slightly increase when comparing mixtures A and B. The difference in mixtures A and B lies in the particle size fractions of the grains. 90 % of the grains of mixture A are shared in the fractions of 2/5 mm and 5/8 mm while 90 % of the grains of mixture B are in the fraction of 2/5 mm. However, mixture C with 50 % in the fraction of 0/2 mm has the highest air entry value.

Taking into account the porosities from the μCT-scans, the residual states were directly derived from the amount of water flown out of the specimen after applying the maximum suction of only 2 kPa. When comparing mixtures A and B, it should be noted that mixture B shows a higher residual saturation at about 0.25, whereby the one of mixture A is about 0. Mixture C, however, shows a slight negative residual saturation. This could be the result of the fact that inaccessible pore content was taken into account when calculating the porosities from the μCT-scans and thus the pore content and corresponding degrees of saturation might be shifted to lower values.

Figure 5 includes the results from the drainage experiments. In addition, results obtained from experiments following the hydraulic imbibition path are added to the figure. Following the theory of porous media, these curves are shifted to the left and show a reduced S_r for suction s = 0 kPa. It should be noted that the higher the specific surface of the particles, i. e. more particles in particle fractions with lower diameter, the lower the degree of saturation that is reached after imbibition. These values could be explained by higher amounts of entrapped air inside the porous structure. Further tests on unbound material of mixture A were performed but showed nearly no retention behaviour (<0.05 kPa) and therefore are not discussed further in this contribution.

3.2 *Fitting*

For better visualisation and further usage of the data in numerical analyses fitting of the obtained data to the commonly used model by van Genuchten (1980) to describe the water-retention behaviour of soils has been performed. The three-parameter function to calculate the effective degree of saturation S_e (-) from a suction s (kPa) is given in equation 1. In the case of this study, the exponent m will be expressed as m = 1-1/n as proposed by Mualem (1976) reducing the equation to a two parameter function. Results of the fitting procedure are presented in table 2.

$$S_e(s) = \frac{1}{(1+(\alpha \cdot s)^n)^m} \quad (1)$$

Equation 2 allows the conversion from effective saturation S_e, sometimes also called normalised saturation, to the actual saturation S_r, which is mainly used in this study.

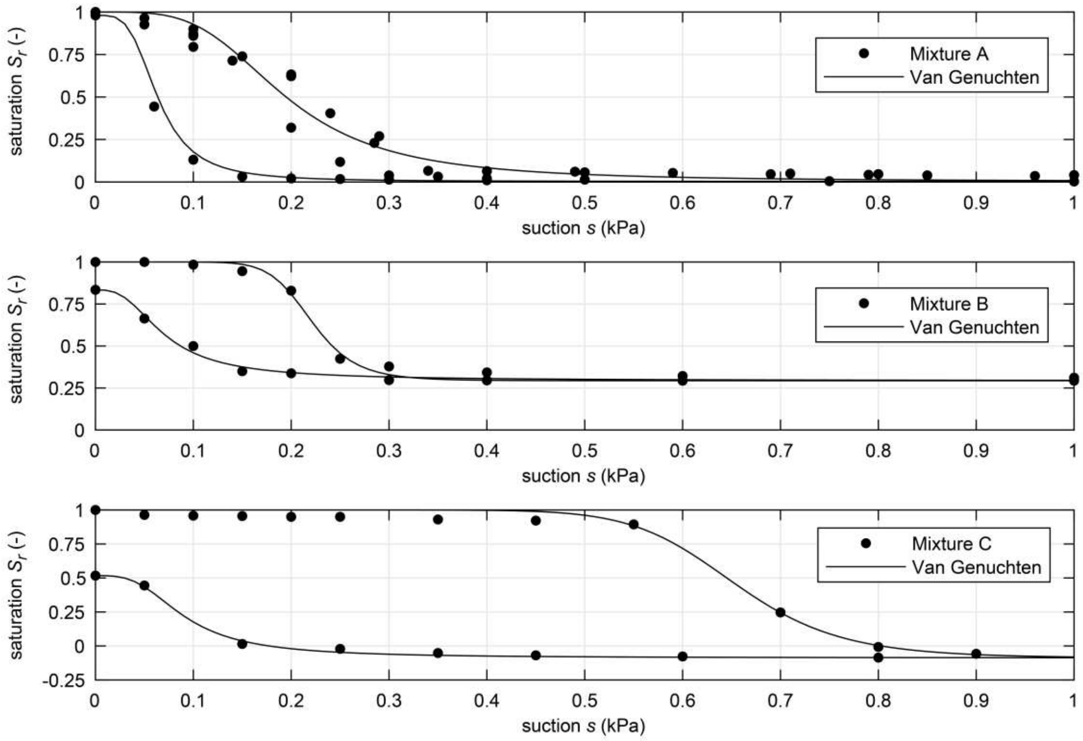

Figure 5. Retention behaviour of the three investigated mixtures A, B, and C obtained from drainage and imbibition experiments. Fitted curves using the model by van Genuchten (1980) are also depicted.

In addition, the authors believe that the presentation of saturation data in terms of actual saturation S_r is more descriptive compared to depicting the data in a normalised form, i. e. in terms of effective saturation S_e.

$$S_r = S_e(S_{r,\max} - S_{r,\text{res}}) + S_{r,\text{res}} \tag{2}$$

For the calculation of the degree of saturation S_r with equation 2, the residual saturation $S_{r,\text{res}}$ has been set to the minimum saturation value from the conducted experiments. $S_{r,\max}$ was set to 1.

Table 2. Hydraulic parameters for the model by Van Genuchten (1980) for the three mixtures A, B, and C.

Model parameters by van Genuchen (1980)	unit	mixture A	B	C
drainage				
a	(1/kPa)	5.70	4.59	1.54
n	(-)	4.02	10.20	12.41
m = 1-1/*n*	(-)	0.75	0.90	0.92
imibition				
α	(1/kPa)	17.32	17.32	12.86
n	(-)	4.00	2.93	3.28
m = 1-1/*n*	(-)	0.75	0.66	0.70

4 SUMMARY AND CONCLUSIONS

The water-retention behaviour of three different water-permeable polyurethane-bound pavement compositions (mixtures) has been investigated in this study. These pavement materials are used in water-permeable road structures to maintain instantaneous infiltration of water into the construction and soil layers beneath. An alternative binder material made from polyurethane has been used to improve the fatigue and deformation behaviour under mechanical loads compared to commonly used bitumen-based porous asphalts.

The analysed materials vary concerning their particle size distributions and pore contents. For the determination of the water-retention behaviour in the low suction range, the method of the hanging water column was utilised. It was shown that the whole range of suction in which the investigations were conducted including the air entry values of the materials are very low, i. e. lower than 1 kPa. The main drainage path starting from fully saturated conditions as well as the imbibition path following after the controlled drainage were investigated. Further, the obtained data was fit to the Van Genuchten (1980) model. The corresponding residual states in terms of water and air content after drainage and imbibition, respectively, become apparent. It is shown that the air entry value as well as the amount of entrapped air after imbibition is dependent on the the particle size distribution, i. e. the composition of the mixtures. The binder amount of the PU might further influence the pore size distribution and thus the retention behaviour. This study, however, focuses on a constant binder content.

As only specimens with a height of 10 mm were tested on their retention behaviour, it is still questionable if the outcome of the experiments can be transferred to a whole pavement layer as it is used in permeable pavement structures, which may have a thickness of 100 mm. However, the expected low capillary effects and retention behaviour of the porous structure can influence the hydraulic performance, such as infiltration rates and the coefficient of the unsaturated hydraulic conductivity.

The determination of a convenient composition of a pavement layer for water-permeable road constructions is highly dependent on the underlying base and subbase courses and needs to be further investigated. All layers of the road construction interact in a hydro-mechanical way and thus need to be calibrated in terms of hydraulic and mechanical performance. This research paper gives a basis for further numerical analyses considering unsaturated states of the pavement layers in the design process of water permeable road constructions.

For further studies, the determination of the effective, i. e. accessible, pore content is a major task. The effective pore content has a direct influence on the mixtures' retention behaviour, as it is directly used to calculate the degree of saturation S_r. Although the investigated effects seem to be negligible, the relevance of the investigated hydraulic properties of water-permeable pavements on drivability, comfort and safety still needs to be evaluated in further tests. In addition, the aforementioned interaction of water-permeable pavement material with granular base and subbase courses and subsoil is still unknown. Taking into account hydraulic and mechanical loads and unsaturated states in full scale tests and numerical analyses is planned to be investigated in the future. Further, the relevance of clogging of the pores due to dirt and other pollutants and the herewith associated reduction of the permeability and changes in the water-retention behaviour of water-permeable pavements could be investigated in the future.

5 ACKNOWLEDGEMENT

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