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Investigation of the Permeability of Fibre-Modified Water Permeable Asphalt with Methods of Asphalt Petrology

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Abstract - The benefits and properties of porous asphalt (PA) pavements were summarised with a literature review. Further, the influence of modifications using different combinations of carbon and cellulose fibre was shown by laboratory tests carried out by the Institute of Transportation Infrastructure Engineering (ITIE) of Technical University of Darmstadt (TU Darmstadt). This paper studies PA's permeability by using asphalt petrology, a geological method adapted for analysing the internal structure of asphalt samples. This method introduces new parameters, such as the void surface area subdivided into classes. These parameters allow further attributes of the asphalt to be inferred, such as vertical permeability. To this end, a function to predict the permeability of asphalt specimens was successfully developed and applied.

***Keywords*:** Asphalt petrology, permeability, fibre modification, air voids

1. Introduction
1.1. Motivation and research goals
The growth of urban areas with sealed surfaces at the expense of permeable natural surfaces has led to increased flooding, loss of urban infrastructure, and non-point pollution [1, 2]. Furthermore, the sizable share of impermeable surfaces alters the natural water cycle in urban areas [3]. The pores in PA are higher in volume and more interconnected compared to conventional asphalt [4]. PA can reduce diffuse pollution by filtering rainwater through permeable layers [1] and gradually returning it to the natural water cycle [5]. Also, PA can manage even intense rainstorms [6, 7], preventing infrastructure from becoming hazardous or unusable. PA improves traffic safety due to reduced surface water and higher skid resistance [8]. Furthermore, PA improves visibility by reducing splash and spray of rain water by 90 % and 95 %, respectively [9]. In warm and humid climates, PA reduces the Urban Heat Island Effect (UHIE) as the water within the pores evaporates with increasing ambient temperature and cools the surroundings [10]. The UHIE increases temperatures in urban areas due to the thermophysical properties of the materials used in the "built environment". This adversely affects the materials as well as the ecology and health of people in the area [10]. The ITIE of TU Darmstadt has conducted research on the vertical permeability of porous asphalt via asphalt petrology methods in lieu of the more laborious methods currently in use. Asphalt petrology offers many insights into the inner structure of asphalt, such as the aggregate's contact angle, distribution and orientation. It can provide an accurate estimate of asphalt's void content-related characteristics, such as vertical and horizontal distribution of voids, which the more common immersion weighing method fails to provide. Asphalt petrology can also indicate the presence of a weak layer bond caused by large accumulations of air voids [11]. Therefore, it is an efficient method of rapidly analysing different PA mixtures and improving their performance.

1.2. Modification of PA
PA has a critical drawback: raveling – a loss of surface material over time due to PA's reduced durability compared to densely graded asphalt [12]. Different materials such as cellulose, polypropylene, polyester, glass, mineral, and carbon fibre [13, 8, 14] can improve asphalt performance. Cellulose fibres have a high surface area, allowing them to bind more bitumen [15] and preventing draining down [5]. Afonso et al. [17] found that the rutting resistance was improved due to the high binder absorption but raveling resistance was not. In fact, cellulose fibres negatively affected particle loss in Cantabro tests. Several authors investigated carbon fiber [18, 19] to improve its mechanical and thermophysical properties. The addition of carbon fibre reduces asphalt's air void content while improving its stability and deformation resistance [20, 21]. However, Gupta et al. [5] found that fiber has a slight negative effect on the permeability of PA. Sediments can clog and thereby reduce

the permeability and noise absorption of PA [22, 12]. This is because some permeability is needed, which water permeable asphalts (WPA) provide at lower mechanical resilience than other PAs [23].

1.3. Methods for determining permeability

Falling and constant head tests are used to determine the permeability of PA. Both tests use a water column placed in the standpipe on the test specimen. For more permeable asphalts used to transmit water, Cooley [25] recommends constant head tests which keep the head constant, measure drainage and calculate the coefficient of permeability with Darcy's Law [26]. In addition to these direct attempts, analytical models have also been proposed. Alomari et al. [27] used the Kozeny-Carman equation to calculate the permeability of hot mix asphalt (HMA) based on the air void (AV) content. AV content, tortuosity of flow paths and a surface area parameter were necessary for this computation. Using the same equation, Masad et al. [28] found that AV content and average particle size are the most important factors. Alvarez et al. [24] studied binder content by including the diameter of bitumen-covered aggregate, and found that crumb rubber-modified asphalt mixtures need more AV to attain a similar level of permeability as mixtures without this modification. For fibre, Afonso et al. [17] reported an improved permeability after applying cellulose fibre, while Lyons et al. [16] found a reduced permeability. Król et al. [29] found that X-ray computed tomography (CT) could determine the permeability of asphalt based on the internal microstructure of PA. Middendorf et al. [30] noted that CT is suitable only for highly specialized cases due to its cost, know-how and equipment requirements.

1.4. Asphalt Petrology

Asphalt petrology is a geology-based method initiated by the Danish Road Institute in the 1990s [31]. The ITIE of TU Darmstadt has been developing micro-section analysis of asphalt since 2017. First, the sample is cut using a precision saw and placed in a mould made of foil. Then, it is placed in a vacuum chamber with fluorescent pigmented epoxy resin that penetrates even the smallest cavities under negative pressure. The finished specimen (cf. Figure 1) is scanned with UV LEDs. Using the open-source software JMicroVision [32], the fluorescent voids are delineated via colour thresholding. Using an object recognition algorithm, contiguous pixels are classified as voids. Methods are described in [11].

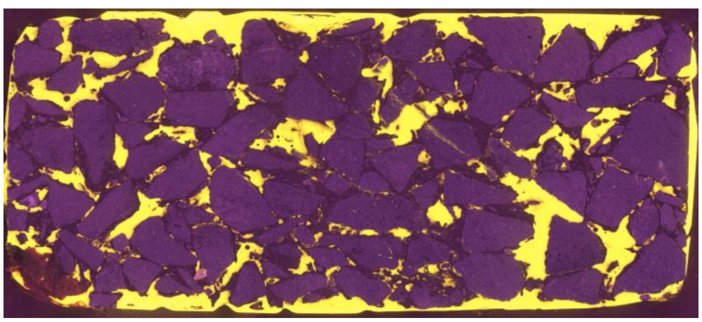

Figure 1: Example of a specimen prepared for asphalt petrology

2. Laboratory Program

Figure 2 shows the laboratory program investigating relationships between void classes, area voids, and permeability of asphalt specimens. Grey shade indicates mix preparation, red indicates specimen preparation, and blue indicates testing.

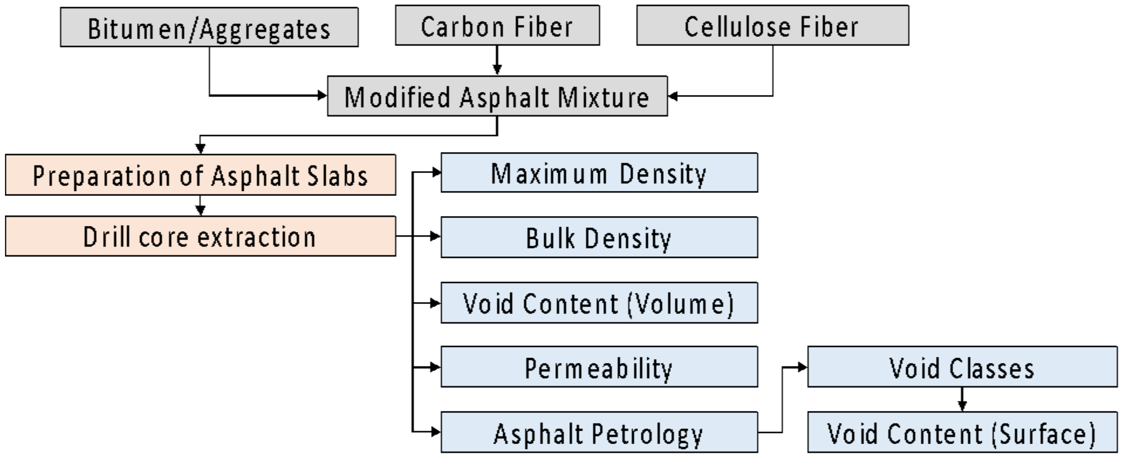

Figure 2: Overview of the laboratory program - mix preparation (grey); specimen preparation (red); testing (blue)

PA 16 is modified with cellulose to limit drainage of bitumen and with carbon fibre to enhance its durability and temperature conductivity while maintaining a sufficient level of permeability. Fibre compositions of different mixtures and the corresponding densities as well as void content for the PA 16 WDA are displayed in Table 1.

Table 1: Composition of the asphalt mixtures produced

Asphalt Mixture	Cellulose fibre content [%]	Carbon fibre content [%]	Maximum density [g/cm^3]	Bulk Density [g/cm^3]	Void Content (Volume) [%]
M1	0.50	0.00	2.859	2.076	27.4
M2	0.40	0.10	2.706	2.103	22.3
M3	0.30	0.20	2.806	2.13	24.1
M4	0.20	0.30	2.792	2.145	23.2
M5	0.10	0.40	2.719	2.105	22.6
M6	0.00	0.50	2.765	2.103	24.0

PA's effectiveness can be evaluated based on its vertical permeability, which is measured according to the German guideline TP Asphalt-StB Part 19 that supplements the European standard EN 12697 [26]. To mimic a real use case, water streams through the asphalt specimen during permeability tests. Following the permeability tests, asphalt petrological sections were prepared. Void classes were defined based on the scanned sections as well as data in Figure 5, and the corresponding void surface area was determined.

3. Evaluation of the results

3.1. Laboratory Results

Figure 4 shows the results of the permeability tests. These are mean values from three individual measurements in each case. Mixes M1 and M3 have the highest permeability at 1.29 mm/s. The mean standard deviation for all mixes is 0.059 mm/s. Since multiple aggregates larger than 11.2 mm were used, there is a minimal amount of mastic or finely granulated material inside the mixture, which causes inhomogeneity. Although void content might be the same across the mixtures, voids in the specimens can differ in composition, size and tortuosity, leading to variations in permeability. Since the same drill cores were used for the permeability and asphalt petrological tests, these variations occur at equal rates.

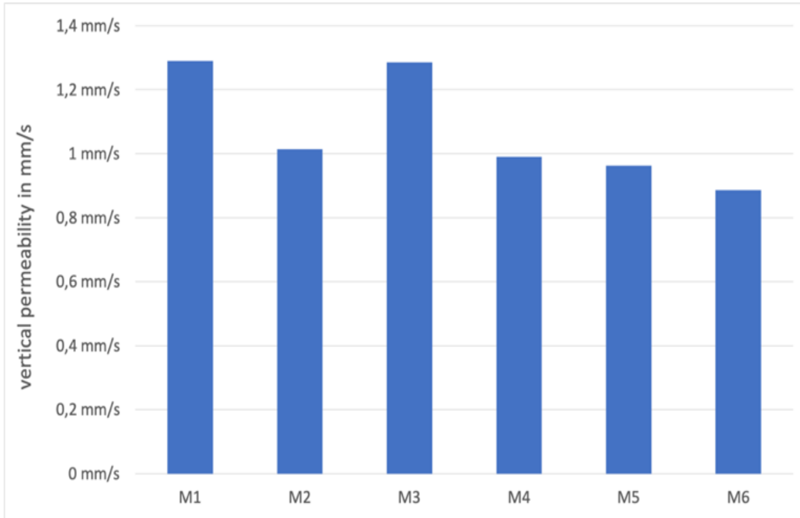

Figure 4: Vertical permeability of asphalt mixtures M1 to M6

EN 12697 [26] proposes a permeability value of 0.5 mm/s to 3.5 mm/s for PA in surface layers. Since the values of the PA are within the given limits, it can be assumed that all asphalt mixtures are suitable for a PA application. Masad et al. [28] stated that void content significantly impacts the asphalt's permeability. Any correlations between void content and permeability as well as between bulk density and permeability were investigated. Three polished sections were prepared for each mixture, and void surface area was calculated based on the arithmetic mean using asphalt petrology. To further differentiate, void surface area was divided into six classes, each representing a defined range of void sizes (cf. Figure 5). Figure 5 shows that, at an average of 39.23 %, class D makes up the largest share of the void surface area. Class A, with void surface area between 0.05 mm^2 and 0.1 mm^2, is the smallest class with a share of 0.024 %. Voids with an area smaller than 0.05 mm^2 were not considered. The following section examines void classes' share and their correlation to the mix types' permeability.

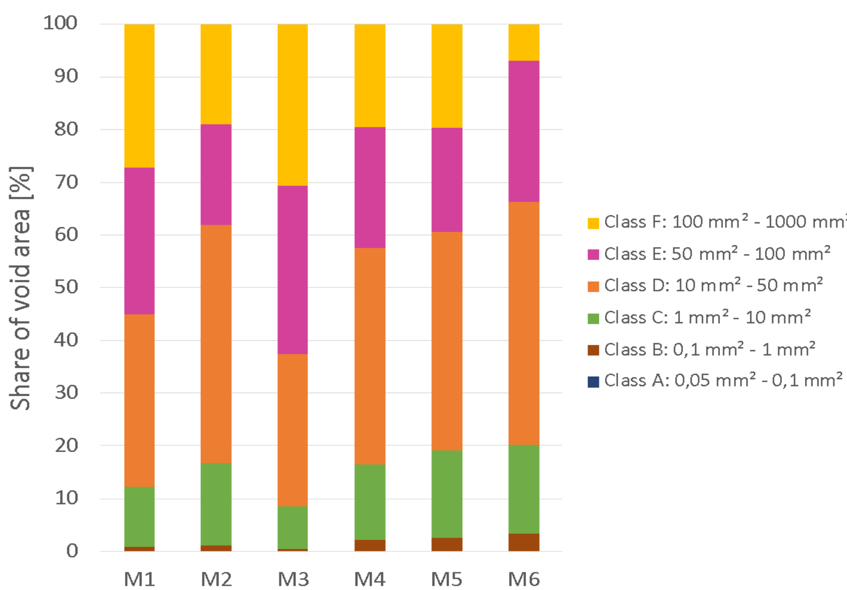

Figure 5: Share of the void classes A to F for the asphalt mixtures M1 to M6

3.2. Correlation study

Singular linear regressions were used to test correlation between asphalt properties and permeability using equation (3), where FR is the permeability in mm/s, VC is the void content as a percentage, β_1 and β_2 are regression constants.

$$FR(VC) = \beta_1 + \beta_2 \cdot VC \tag{3}$$

First, single linear regression of bulk density and void content produced the red dotted lines in Figure 6. With a coefficient of determination of $R^2 = 0.0326$, no correlation could be shown. Next, analysing flow permeability and void content produced a poor correlation with a coefficient of determination of $R^2 = 0.4577$. Simplifying Masad et al. [28]'s relationship between void content and permeability via a singular linear regression was not possible.

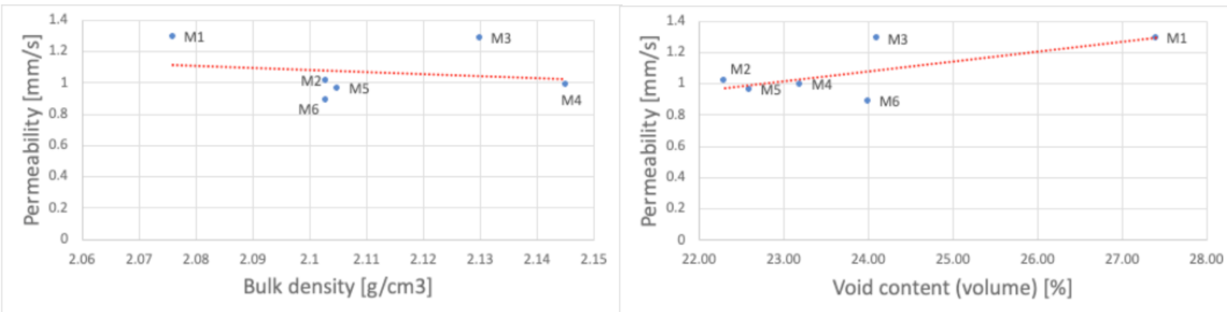

Figure 6: Correlation between bulk density(left) / void content (right) and vertical flow rate for mixes M1 to M6

Next, any correlation between respective void surface area of the defined classes (cf. Figure 5) and permeability was studied using equation (3). Red dotted lines in Figure 7 show regressions for void classes A to F. Classes B, C, D and F (cf. Table 3) have coefficients of determination above 75 %. Class A was not considered due to its small size and share.

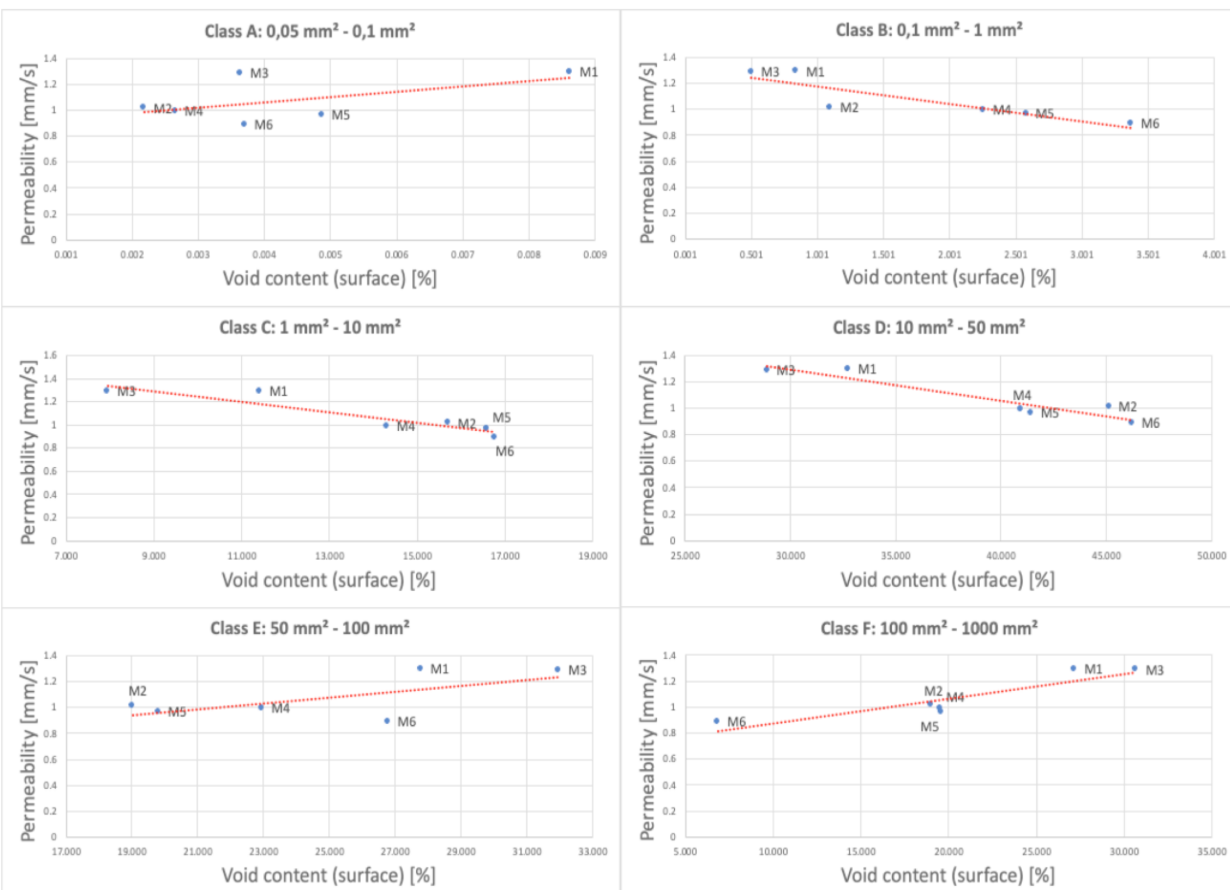

Figure 7: Correlation between the share of the void area and flow rate for void class A to F for asphalt mixes M1 to M6

For the smaller void classes B, C and D, an inversely proportional relationship is observed where the gradient of the regression line is negative. As the share of void surface area increases, the permeability decreases, which sounds contradictory at first. However, the increase in the void surface area of the smaller classes B, C, and D means that the void area content increases in the larger void classes E and F. For these larger classes, there is a proportional relationship to permeability where the gradient of the regression line is positive. It can be concluded that larger void classes are most important in assessing permeability.

Table 3: Results for the coefficient of determination from the single linear regression (void surface area content/permeability) for mixes M1 to M6

Void Surface Area Class	Individual coef. of Determination (R^2)
A	0.304
B	0.774
C	0.855
D	0.885
E	0.430
F	0.816

The relationship between permeability and different void classes suggested that a function needs to consider all relevant void classes to be useful. A multiple linear regression with equation (4), which does not contain a regression intercept unlike equation (3), was used to investigate the overall correlation between void classes and permeability. Thus, the function intersects the Y-axis at the zero point since the flow rate must be 0 mm/s for a total void content of 0 %. Void class A was excluded from the regression analysis for the reasons detailed before. The results are in Table 4.

$$FR(VC) = \beta_1 \cdot VC_B + \beta_2 \cdot VC_C + \beta_3 \cdot VC_D + \beta_4 \cdot VC_E + \beta_5 \cdot VC_F \quad (4)$$

The more independent variables were included in the model, the higher the coefficient of determination. This was independent of whether the additional independent variables contribute to explaining the correlations. Therefore, the adjusted coefficient of determination was used to assess the quality of multiple regression models. In contrast to the simple coefficient of decision, the adjustment considers the number of independent variables in the model [33]. For the correlations examined, a very high adjusted coefficient of determination at cap $R^2 = 0.998$ was found.

Table 4: Results of the multiple regression (share of void area/flow rate) for asphalt mixes M1 to M6

Void Surface Area Class	Regression Constant	Adjusted Coef. of Determination (R^2)	Significance
B	β_1=-0.113		
C	β_2=-0.061		
D	β_3=-0.012	0.998	0.023
E	β_4=+0.028		
F	β_5=+0.011		

The F-test can be used to see whether the regression model is statistically significant. It tests if the predictive value of the dependent variable is improved by adding the independent variable [34]. At 0.023, the significance value is relatively small and is below the maximum alpha value of 0.050 usually defined for statistical evaluation of test methods [35].

4. Conclusion

To our knowledge, this study is the first to determine permeability by analysing the void surface area using asphalt petrology. Asphalt petrological investigations have shown a significant correlation between void surface area and the permeability of a corrugator sample. To test this correlation accurately, it is necessary to differentiate air void surfaces into five or six void classes. As the share of smaller cavity classes decreases, the share of larger cavity classes increases, which in turn increases the permeability of the specimen. However, these results apply only to vertical permeability and not to horizontal permeability. Moreover, the tests were carried out only on fibre-modified WPAs under constant temperature conditions. Even though the overall significance of the correlation is acceptable at 0.023, the individual significance values of the regression parameters β_1 to β_5 with an average of 0.249 indicate room for improvement. Therefore, further investigations with more samples and mixture types under different conditions are recommended. It is conceivable to improve the predictive power of the equation by adding constants that take into account flow direction and temperature, among others. Additional validations of this paper need to be carried out using specimens from construction sites to determine possible deviations in field applications.

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