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Assessing the hydraulic conductivity of road paving materials using representative pore size and grading entropy

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Abstract: Pavements are ubiquitous civil engineering structures which form the important lifelines that connect communities. They must remain serviceable after events such as flooding, cyclones and extreme freeze-thaw cycles. The hydraulic conductivity of road pavements is important to understand their performance. This paper summarises some recent work aimed at improving the prediction of the hydraulic conductivity of asphalt concrete. Laboratory test results show the use of the 'hand pumping method' to measure the percentage of connected air voids in asphalt concrete specimens. The representative pore size concept is used to analyse an updated database of hydraulic conductivity measurements of asphalt concrete. The effect of nominal maximum aggregate size is studied. Preliminary efforts to use the grading entropy framework to predict the hydraulic conductivity of asphalt concrete are reported.

Keywords: Asphalt concrete; Hydraulic conductivity; Representative pore size; Grading entropy

1 INTRODUCTION

Water can negatively affect the mechanical properties of pavements (e.g., Caro et al. 2008a, Caro et al. 2008b). These negative effects are generally manifested as stripping, ravelling and permanent deformation (e.g., Kutay et al. 2007, Dawson et al. 2009, Aboufoul and Garcia 2017). Prolonged moisture saturation can induce damage, leading to an increase in the oxidation process of asphaltic binders which can adversely impact pavement durability (e.g., Abdullah et al. 1998, Dawson et al. 2009). Dynamic traffic loads on a saturated surface can also cause excessive pore water pressure and lead to damage of the pavement structure (Thom 2014). Taking these factors into consideration, there is the need to assess and effectively control the hydraulic conductivity during the design and construction process, to prevent moisture ingress and to achieve optimal durability and service quality of the road structure. Many published studies (e.g., Waters 1990, Waters 1998, Mallick et al. 2003, Vardanega and Waters 2011, Vardanega 2014) indicate that the level of air voids is a key factor affecting the hydraulic conductivity of asphalt concrete.

2 LABORATORY TESTING

A series of laboratory tests have been conducted on seven asphalt concrete samples. The test methods employed are given in Table 1. The results of the laboratory experiments are listed in Table 2 (see Feng 2017 for further details of the laboratory testing).

Table 1. Summary of test method used in laboratory testing

Measured parameters	Method used	Note
Hydraulic Conductivity (k)	Ponding method (DTMR 2014)	
Bulk density	BS 1377-2:1990 (1990)	
Maximum density	WA732.2-2011 (2011)	
Open air voids	Hand pumping method (Smith and Gotolski 1969)	Cupping one hand over the sample and using the palm as a plunger to pump the air out of the voids is done as part of the process

Table 2. Test results of asphalt concrete samples (reported in Feng 2017)

Sample	Test Side*	T(°C)	k (mm/s)	Category**	AVtotal (%)	AVopen (%)	α***
DD2-1	Coarser	20.9	3.80×10^{-1}	D	11.29	10.03	0.89
	Smoother	21.2	3.40×10^{-1}	D			
DD2-2	Coarser	21.3	1.38×10^{-1}	D	13.32	9.34	0.70
	Smoother	21.3	1.60×10^{-1}	D			
DD5-2	Coarser	21.2	0	A1	3.00	2.23	0.74
	Smoother	21.8	0	A1			
TSC T2.4-1	Coarser	21.8	0	A1	10.91	6.22	0.57
	Smoother	21.2	0	A1			
TSC T2.4-2	Coarser	21.2	2.00×10^{-3}	B	9.62	6.82	0.71
	Smoother	19.9	7.51×10^{-3}	B			
591-1	Coarser	19.7	0	A1	4.44	3.65	0.82
	Smoother	21.2	0	A1			
591-2	Coarser	21.2	0	A1	4.17	3.09	0.74
	Smoother	21.2	0	A1			

* 'Coarser' indicates that hydraulic conductivity was measured with coarser side of asphalt core up; 'Smoother' indicates that hydraulic conductivity was measured with smoother side of the asphalt core up.

** Hydraulic conductivity category details can be found in Vardanega and Waters (2011)

*** α = Degree of conductivity = AVopen divided by AVtotal.

By measuring the total air voids (AVtotal) and the open (connected) air voids (AVopen), the degree of conductivity, which is the proportion of total voids connected to the open air (AVopen divided by AVtotal) can be calculated (see Table 2). Figure 1 shows the k values measured from smoother and coarser sides of the sample against total air voids (Fig. 1a) and open air voids (Fig. 1b). Fig. 1(a), shows that an increase in k does not always correspond with an increase in AVtotal, while Fig. 1(b) shows that as k rises, so too does AVopen. While AVopen is superior for the prediction of k, many studies do not quote this parameter. The next section shows the use of the representative pore size concept for prediction of hydraulic conductivity of asphalt concrete. It could be argued that if a database of hydraulic conductivity with corresponding AVopen measurements was available, the strength of correlations of the form developed in the next section may improve.

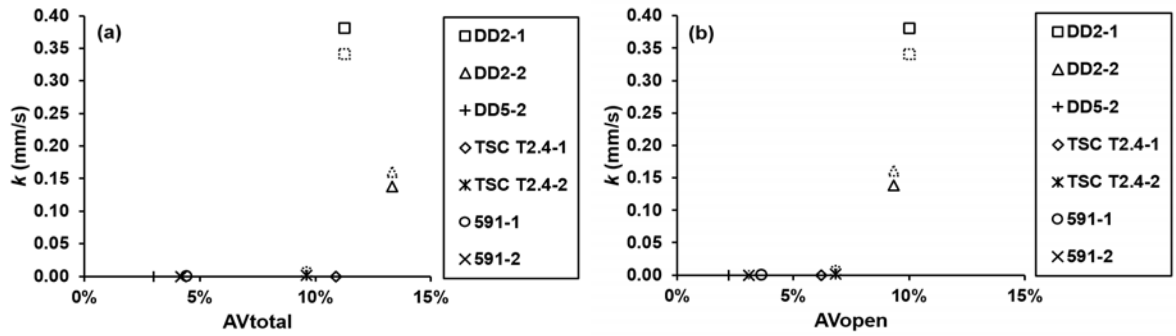

Figure 1. k versus (a) AVtotal and (b) AVopen (both expressed as percentages). k measured from the coarser side of the specimen denoted by solid lined icons while k measured from the smoother side denoted with dashed lined icons)

3 DATABASE ANALYSIS: REPRESENTATIVE PORE SIZE CONCEPT

Vardanega and Waters (2011) proposed the representative pore size (R_p) concept which is similar to the normalised voids approach (Waters 1998). Both approaches account for the influence of an effective particle size (D_{eff}) when making predictions of hydraulic conductivity of asphalt concrete (N.B. R_p = 2/3×Air voids(%)/100×D_{eff}).

Vardanega and Waters (2011) compiled a database of hydraulic conductivity measurements on asphalt concrete and regressed R_p with k thus producing Eq. (1). For Eq. (1) the R^2 (coefficient of determination) was 0.74, with an n (number of data points used in the correlation) equal to 467. In Eq. (1), D_{75} (the sieve aperture through which 75 percent of the material would pass) was chosen as the D_{eff} based on statistical analysis. D_{75} is used to compute R_p in the following analyses shown in this paper.

$$k = 0.46(R_p)^{3.7} \qquad R^2 = 0.74,\ n = 467 \qquad (1)$$

Vardanega et al. (2017) expanded the database from Vardanega and Waters (2011) and presented a revised version of Eq. (1) shown here as Eq. (2).

$$k = 0.193(R_p)^{3.58} \qquad R^2 = 0.55,\ n = 1318 \qquad (2)$$

The database presented in Vardanega et al. (2017) was further expanded by Feng (2017). The updated database now has over 1500 data points (see Feng 2017 for further details of the sources of the data in the database). When compiling the database, samples without percentage air voids quoted or with zero hydraulic conductivity were eliminated as they could not be employed in regression analysis when using power-law fitting models. Eq. (3) shows the revised result of the regression between R_p and k for the expanded database presented in Feng (2017):

$$k = 0.17(R_p)^{3.425} \qquad R^2 = 0.60,\ n = 1578 \qquad (3)$$

The nominal maximum aggregate size (*NMAS*) value was generally available from the collected publications. For those subsets without an assigned value, the *NMAS* values were estimated based on the provided gradation curves. Yan et al. (2016) suggested that the hydraulic conductivity of the asphalt mixture can be influenced by both the air voids level and *NMAS*. Vardanega et al. (2017) divided the database (n = 1318) into two data sets (*NMAS* ≤ 12.5mm and *NMAS* > 12.5mm) and concluded that the influence of *NMAS* was minimal but statistically detectable. Using the expanded database of Feng (2017) (n = 1578), three data sub-sets were established: *NMAS* equal or less than 9.5mm; between 9.5mm to 12.5mm and larger than 12.5mm. The results from the regression analysis of the aforementioned data sub-sets are shown in Table 3.

Table 3. Regression results of sub-divided data-sets (regression plots shown in Feng 2017)

NMAS	Equation	R^2	n
$NMAS \leq 9.5$mm	$k = 0.92R_p^{4.57}$	0.63	305
9.5mm $\leq NMAS \leq$ 12.5mm	$k = 0.19R_p^{3.37}$	0.61	742
$NMAS \geq 12.5$	$k = 0.12R_p^{3.61}$	0.62	531

According to the results in Table 3, *NMAS* has a minor influence on the R^2 value for the regression results, but it does have some effect on the exponent and coefficient of the equations in Table 3 (cf. Eq. 3 and Vardanega et al. 2017). The next section shows the preliminary results of analysing the same database use the grading entropy framework (e.g., Lőrincz et al. 2005 and Singh 2014).

4 DATABASE ANALYSIS: GRADING ENTROPY FRAMEWORK

4.1 Grading Entropy Theory

The grading entropy theory is attributed to Lörincz in 1986 (Lőrincz et al. 2005 and Singh 2014) which considers the particle size distribution as a reflection of its disorder. The relative frequency of fraction i, x_i, is:

$$x_i = \frac{M_i}{M} \tag{4}$$

where M_i is the weight of the particles in fraction i (which is equivalent to the percentage of particles retained in the sieve) and M is the total weight of the sample mixture. The number of elementary cells in a fraction i, C_i, is:

$$C_i = \frac{d_{i+1} - d_i}{d_0} \tag{5}$$

where d_0 is the width of the elementary cell, and d_i is the width of the fraction i.

Therefore, the grading entropy of a granular mixture can be expressed as:

$$S = -\sum_{i=1}^{N} x_i \log_2 x_i + \sum_{i=1}^{N} x_i \log_2 C_i = \Delta S + S_0 \tag{6}$$

where ΔS is the entropy increment and S_0 is the base entropy. By constraining the base entropy S_0 to 'a fixed interval for a different number of fractions' (Singh 2014), and making the entropy increment ΔS independent with N, two normalised entropy coordinates - relative base grading entropy, A, and normalised entropy increment, B - are obtained:

$$A = \frac{\sum_{i=1}^{N} x_i(i-1)}{N-1} \tag{7}$$

$$B = -\frac{\sum_{i=1}^{N} x_i \log_2 x_i}{\log N} \tag{8}$$

By using *A* and *B*, any grading curve can be plotted as a single point on the normalised entropy diagram.

4.2 Analysis Results

An early preliminary study at the University of Bristol (James 2015) used a small database (n = 77) to study the hydraulic conductivity of asphalt concrete using grading entropy and air void levels. In this section, the expanded asphalt concrete database from Feng (2017) (n = 1578) is analysed using the grading entropy framework (Fig. 2) to see if the hydraulic conductivity of asphalt concrete pavement material can be understood a priori without the need for air voids measurement. The particle size distributions of the asphalt concrete mixes represented in the database were used to compute the normalized grading entropy coordinates (*A* and *B*) using Eqs (7) and (8). Based on the multiple linear regression results of the whole database, relations of the form $k = xA^yB^z$ and $k = e^{xA+yB+z}$ proved to be statistically superior. In keeping with earlier analysis on gravel (see Feng 2017 for further details), $k = xA^yB^z$ is used in this paper. The correlation found linking *A, B* and *k* can be expressed as:

$$k = 0.84A^{11.71}B^{-2.73} \qquad R^2 = 0.20,\ n = 1578 \tag{9}$$

While Eq. (9) is not as strong statistically as Eq. (3), it is statistically significant ($p < 0.001$) and does not require the measurement of air voids.

5 SUMMARY

(a) This paper has presented the results of laboratory testing of seven asphalt concrete cores and provides some further evidence that the AVopen (measured using the 'hand-pumping method') is superior to AVtotal as a measure of porosity linked to *k*.

(b) Regression analysis of an updated database of over 1500 measurements of *k* of asphalt concrete has confirmed that the R_p is a good predictor of *k*. The effect on the fitted function and the R^2 when the database is subdivided according to *NMAS* is arguably minimal.

(c) Some preliminary analysis of the database using the grading entropy framework and multiple linear regression analysis has shown that a statistically significant correlation can be found linking *k* to the normalised grading entropy co-ordinates. However, this approach is not as statistically powerful as the representative pore size approach.

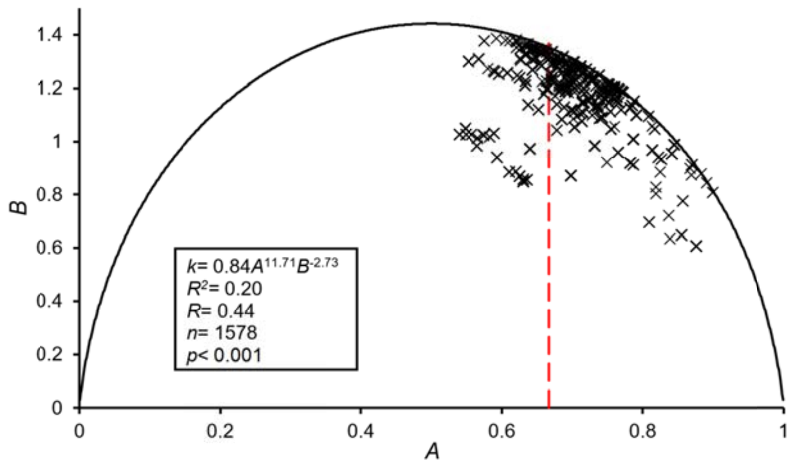

Figure 2. Database plotted on the grading entropy diagram (adapted from Feng 2017) (*A* = 2/3 line shown)

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