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A New Model on the Hydraulic Conductivity of Asphalt Mixtures

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Abstract: It is well known that asphalt mixtures with different air void contents will present different drainage capacity, but until now there is not a model that evaluates its water infiltration capacity considering its air void content value. For this reason, a new model to predict the hydraulic conductivity (permeability) of asphalt mixtures as a function of its air void content has been proposed in this paper. Additionally, this paper presents the laboratory results and procedures used to measure the hydraulic conductivity of asphalt mixtures with a wide range of air void content. With this purpose, four types of asphalt mixtures with different aggregate distribution (dense, semidense, discontinuous and porous), amounts of bitumen (from 4.5 to 5.2%) and air void content (from 4 to 20%), have been tested. The average hydraulic conductivity of the asphalt mixtures analyzed ranged from 5.2×10^{-6} to 3.0×10^{-2} cm/s. Besides, it has been found that the hydraulic conductivity model is valid for all ranges of air void content existing in the compacted asphalt mixture. In addition, the model has been checked through experimental and literature data, presenting a good fit to data. Therefore, the results of this study can be used as reference values of the hydraulic conductivity of asphalt mixtures used in the road pavement construction.

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***Key words**: Air void content; Asphalt mixture; Hydraulic conductivity; Water flow.*

Introduction

The presence of water in asphalt concrete pavements may affect their mechanical properties, reducing their strength, stiffness and durability. Water damage [1] is generally manifested as ravelling or stripping, commonly attributed to water infiltration into the asphalt mixture. This is characterized by the loss of bond between the aggregates and the mastic [2] and currently, there are very few solutions to repair this type of damage [3, 4]. Therefore, the hydraulic conductivity or coefficient of permeability of asphalt mixtures is an important property that should be known, in order to evaluate the water infiltration capacity of asphalt concrete pavements [5]. Hydraulic conductivity in a saturated asphalt mixture is defined as the rate of discharge of water under laminar flow conditions through a cross sectional unit area of porous medium [6]. Its value provides an indicator of the drainage capacity of asphalt concrete pavements under initial construction conditions. In addition, hydraulic conductivity is usually anisotropic; consequently, the hydraulic conductivity in vertical and horizontal directions may have significant differences [7].

In this line, Table 1 presents a review of the main experimental studies [8-20] about the saturated hydraulic conductivity of asphalt mixtures, measured under field and laboratory conditions. In addition, a categorization of the drainage conditions based in the study by Vardanega and Waters [21] is also shown in Table 1. From these studies, it can be observed that the hydraulic conductivity of asphalt mixtures may vary by six orders of magnitude (10^{-7} to 10^{-1} cm/s) for materials with an air void content between 3 and 26 %. In addition, the hydraulic conductivity of dense and semidense asphalt mixtures (10^{-6} to 10^{-2} cm/s) was lower than the hydraulic conductivity of discontinuous and porous asphalt mixtures (10^{-2} to 10^{-1} cm/s), with air void content higher than or equal to 12%. A similar conclusion was also given in the study by Apul et al. [22].

There are different standard test methods [23, 24] used for the laboratory measurement of hydraulic conductivity in asphalt mixture specimens. These methods use a flexible or rigid-wall mould permeameter, for example the Constant Head Method and the Falling Head Method. Furthermore, there are some other test procedures recently published, such as the Florida method [25] and the European standard [26]. The Florida Method is a falling-head hydraulic conductivity test, carried out in an apparatus equipped with a latex membrane that encases the specimen. The European standard is similar to the Florida method, but it is not appropriate for the measurement of hydraulic conductivity of dense or semidense asphalt mixtures, with an air void content of less than 6%; and where the hydraulic conductivity values are lower than the range established by the European standard.

For these reasons, this paper has been prepared to develop a method that can evaluate the hydraulic conductivity of asphalt mixtures in a wide range of air void contents. To reach this objective, a new model to predict the hydraulic conductivity as a function of the air void content has been developed. To check the new model proposed, four types of asphalt mixtures, with different aggregate distribution, amounts of bitumen and air void contents, have been investigated. On the other hand, two types of conventional laboratory tests have been successfully adapted to measure the permeability in asphalt mixtures, within a wide range of air void content: triaxial cell and falling head permeameter.

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Table 1. Critical Review of Hydraulic Conductivity Measurements on Test Samples and its Categorization.

Author	Relevant Information about Specimens			Air-void Content (%)	Hydraulic Conductivity ($\times 10^{-5}$ cm/s)	Category Symbol
	Short Description	NMAS[a] (mm)	Lab/field			
Terrel and Al-Swailmi [8]	Asphalt Mixtures Samples	−	Lab	4−11	0.0−20	V_L&M_P
Choubane et al. [9]	Fine-graded Marshall	−	Field	5.9−8.3	14−52	M_P
	Coarse-graded Superpave	−	Lab	6.5−8.3	22−145	M_P & P
Lynn et al. [10]	Superpave Asphalt Mixtures	−	Lab	3.5−15	10−10000	L_P&M_F
Cooley and Brown [11]	Asphalt Mixtures Samples	−	Field & Lab	−	100−16000	M_P&F
Cooley et al. [12]	Coarse-graded Superpave	−	Field	3−8.6	0.0−275	V_L&P
	Coarse-graded Superpave	9.5	Field	7.7	100	M_P
	Coarse-graded Superpave	12.5	Field	7.7	100	M_P
	Coarse-graded Superpave	19	Field	5.5	120	P
	Coarse-graded Superpave	25	Field	4.4	150	P
Mallick et al. [13	Dense-graded Superpave	−	Field	8.0	60.2	M_P
	Dense-graded Superpave	−	Lab	8.0	97.5	M_P
Fwa et al. [14]	Porous Asphalt Mixtures	−	Field	≥20	≥10000	F
Kanitpong et al. [15]	Fine-graded Superpave	12.5	Lab	4.7−7.3	0.51−3.3	V_L&L_P
	Super Fine-graded Superpave	12.5	Lab	4.6−5.6	0.055−0.66	V_L
	Super Coarse-graded Superpave	12.5	Lab	6−8.4	0.68−55	V_L&M_P
	"S" Shape Superpave	12.5	Lab	6.3−8.1	10−100	M_P
	Crushed Limestone Superpave	12.5	Lab	4.8−9.1	0.17−77	V_L&M_P
	Crushed Gravel Superpave	12.5	Lab	3.2−7.7	0.0071−22	V_L&M_P
Bowders at al. [16]	Fine-graded Marshall	12.5	Lab	3.2−6.3	0.0−2	V_L&L_P
Tarefder et al. [17]	Asphalt Superpave Samples	−	Lab	5.6−7.7	1−36	L_P&M_P
Vivar and Haddock [18]	Coarse-graded Superpave	9.5	Lab	4.2−9.6	0.0−173.54	V_L&P
	Fine-graded Superpave	19	Lab	4.1−11.2	0.0−324.38	V_L&P
Pease et al. [19]	Asphalt Mixtures Samples	−	Lab & Field	4.0−6.8	0.365−9.83	V_L&L_P
Charbeneau et al. [20]	Thin Layers of Porous Asphalt	−	Field	16−26	≥11800	F

Hydraulic Conductivity Range ($\times 10^{-5}$ cm/s)			Description[b]	Symbol
0.1	to	1	Very Low Permeability	V_L
1	to	10	Low Permeability	L_P
10	to	100	Moderate Permeability	M_P
100	to	1000	Permeable to Draining	P
1000	to	10000	Moderate Free Draining	M_F
		>10000	Free Draining	F

[a]NMAS: Nominal Maximum Aggregate Size.
[b]Based on the study of Vardanega and Waters 21.

Materials and Methods

Materials

Four different asphalt mixtures were tested in this study. The different aggregate distributions are shown in Fig. 1. These mixtures were classified in two groups depending on their air void content. Impervious mixtures (dense and semidense), with air void content lower than 6%, and pervious mixtures (discontinuous and porous), with air void content higher than or equal to 12%. In addition, the aggregates used to manufacture the mixtures were ophite (size between 22 and 2 mm and density 2902 kg/m^3), limestone sand (size between 2 and 0.063 mm and density 2708 kg/m^3) and filler (size < 0.063 mm and density 2700 kg/m^3). Furthermore, the bitumen used was B50/70 with density 1033 kg/m^3 for dense (bitumen content 4.6%), semidense (bitumen content 4.5%), discontinuous mixtures (bitumen content 5.2%), and porous mixtures (bitumen content 4.6%).

Test Specimen Preparation

The specimens were prepared according to the Marshall method. In this way, Marshall test samples with 10 cm diameter, approximately 6 cm height and exactly 1190 g of mass were prepared using a mechanical mixer and a Marshall hammer. The number of blows on each face was 75 for the impervious test specimens and 50 for the pervious test specimens. Finally, the dense, semidense and discontinuous asphalt mixtures were subject to a compaction temperature of 150℃, while the porous asphalt mixtures, to a compaction temperature of 170℃.

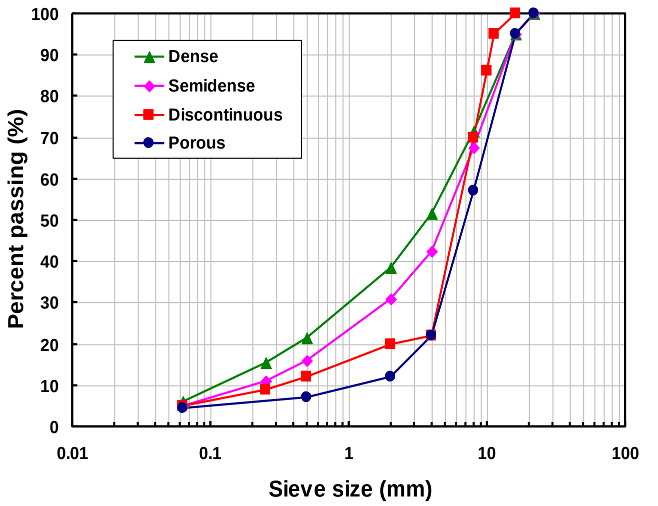

Fig. 1. Mixtures Graded Aggregates Distribution: Nominal Maximum Aggregate Size (NMAS) of 16 mm for Mixtures Type Dense, Semidense and Porous, and 11.2 mm for Discontinuous Mixture.

Physical Characterization of Asphalt Mixtures

The air void content and bulk density were calculated geometrically for all the asphalt mixtures types. With this purpose, the exact height and weight of 6 cylindrical test samples of each type of asphalt mixture were measured to calculate the bulk density of each test sample. In addition, as the exact percentage of materials and their density for each mixture were known, the theoretical density without voids for each mixture could be found. Finally, the percentage of air voids was calculated as:

$$Air void content = \left(1 - \frac{\rho_b}{\rho_t}\right) \cdot 100 \quad (1)$$

where ρ_b is the bulk density of the mixture, and ρ_t is the theoretical density without voids of the mixture.

Hydraulic Conductivity of Impervious Mixtures

The hydraulic conductivity of the test samples dense and semidense asphalt mixtures was measured in a triaxial cell. These tests were performed by following the recommendations of the BS 1377-6 standard [23] (Fig. 2 (a)): Firstly, each test sample of 10 cm diameter and 6 cm height was confined laterally with two rubber-elastic membranes to prevent edge leakage, and to maintain an airtight conditions in the sample until the start of the test. Then, each test sample was placed into the cell between two porous ceramic disks with the same diameter of the specimen, saturated and laterally confined by applying a cell pressure. Table 2 shows the pressure values applied to the upward test samples. After this, the test begins by increasing the bottom pressure, causing an upward water flow through the sample. The pressure difference between the specimen top and bottom caused a hydraulic gradient which, together with the geometrical properties of the sample and the measured water flow rates were used to determine the hydraulic conductivity as:

$$K_i = \frac{\Delta Q L}{A h \Delta t} \quad (2)$$

where K_i is the hydraulic conductivity of impervious mixtures at 20℃, ΔQ is the water flow, L is the height of the test sample, A is the cross-sectional area of the test sample, Δt is the interval of time and h is the difference in hydraulic head across the specimen.

Hydraulic Conductivity of Pervious Mixtures

The hydraulic conductivity of the test samples discontinuous and

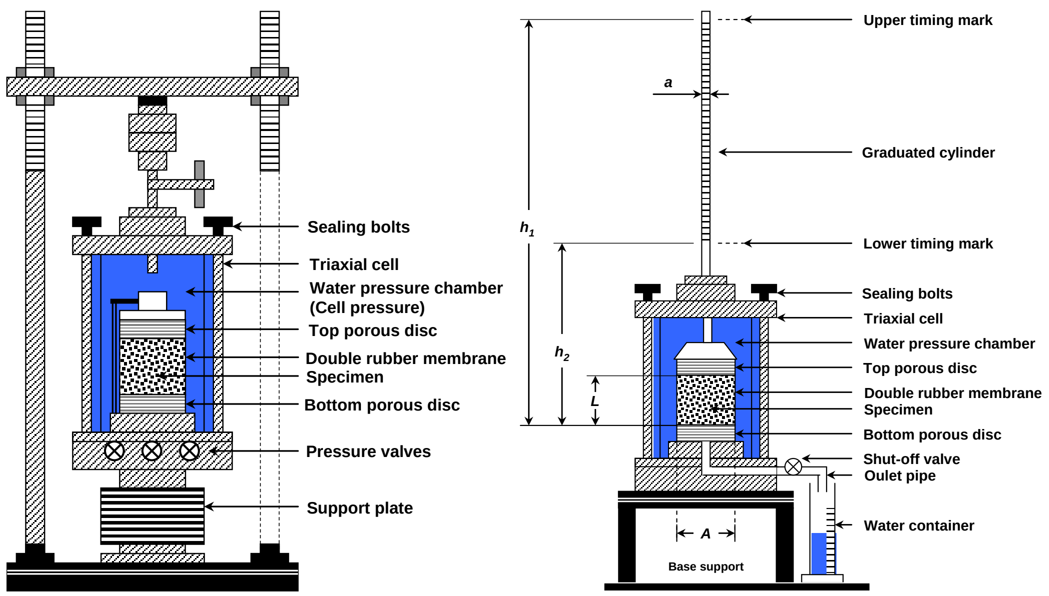

Fig. 2. Hydraulic Conductivity Tests: (a) Triaxial Cell for the Measure in Impervious Mixtures, and (b) Falling Head Test by Using Triaxial Cell and Graduated Cylinder for the Measure in Pervious Mixtures.

Table 2. Pressure Applied to Mixture Test Samples Inside Triaxial Cell (in kPa).

Pressure Type	Impervious Mixtures		Pervious Mixtures	
	Dense	Semidense	Discontinuous	Porous
Cell Pressure	833.8	784.8	686.7	686.7
Top pressure (P_1)	588.6	588.6	588.6	588.6
Bottom Pressure (P_2)	735.8	735.8	n/a	n/a
Cell Effective Pressure	245.2	196.2	98.1	98.1
Average Effective Pressure	171.7	122.6	n/a	n/a
Differential Pressure (P_2-P_1)	147.1	147.1	n/a	n/a

n/a: not applicable pressure.

porous asphalt mixtures was measured following the recommendations of the Method B in the ASTM D5856-95 standard [24] and of the Florida standard test [25] (Fig. 2(b)). With this purpose, test specimens were prepared and saturated following the same procedure described for impervious mixtures, with the pressures shown in Table 2. For the tests, a triaxial cell and a graduated cylinder were used. Once the specimens were saturated and laterally confined in order to prevent edge leakage, the triaxial cell was removed and placed on a base support. Moreover, it was connected to a flexible graduated cylinder; which had an upper and lower mark. In this way, the experiment consisted in recording the elapsed time between the upper and lower marks, while the vertical water flow passed through the test sample. Finally, the water drained through the test specimen was measured. The hydraulic conductivity of each test sample was calculated as:

$$K_p = \frac{aL}{At} ln\left(\frac{h_1}{h_2}\right) \tag{3}$$

where K_p is the hydraulic conductivity of pervious mixtures at 20℃, a is the internal cross-sectional area of graduated cylinder, L is the height of specimen, A is the cross-sectional area of the test specimen, h_1 and h_2 are the initial and final head/ mark (in graduated cylinder) across the test specimen, and t is the elapsed time between h_1 and h_2.

Theoretical Model on the Hydraulic Conductivity

This model has been formulated based on the capillary flow theory into porous materials and considering hypothesis of saturation of the material. So that to characterize water flow through saturated asphalt mixtures, a modification of the Lucas-Washburn equation [28] to describe the capillary flow into porous materials has been used. Consequently, the main force fields that affect water flow inside asphalt mixture are: (1) the surface tension $2\pi r\gamma\, cos(\theta)$, where r is the radius of the asphalt mixture pores through which water moves, γ is the surface tension of the liquid and θ is the contact angle of water, whose value is 90^o in this case, because the material is considered to be saturated (2) the liquid inertia $8\pi\eta h(t)(dh(t)/dt)$, where η is the viscosity of the liquid and $h(t)$ is the distance of the water front to the test sample surface at a time t, (3) the water weight $\rho g h(t)$, where ρ is the density of the liquid and g is the gravity, and (4) the friction of water against the walls of the asphalt mixture pores $2\pi r\beta(dh(t)/dt)$, where β is a parameter introduced to take into account possible sources of energy dissipation. Therefore, the force equilibrium of water in asphalt mixture is defined as:

$$2\pi r\gamma\, cos(\theta) - 2\pi r\beta \frac{dh(t)}{dt} = 8\pi\eta h(t)\frac{dh(t)}{dt} + \rho g h(t) \tag{6}$$

Additionally, to effects of this new analytical approach, as first hypothesis has been considered that hydraulic conductivity of asphalt mixture is measured under saturated conditions, thus surface tension can be neglected. Moreover, water flow through saturated asphalt mixtures can be considered one-dimensional, steady, and laminar [7]. Additionally in reference [29] it is shown that for a non-viscous liquid moving inside a porous media, the inertial term can be neglected. With this in consideration, Eq. (6) can be rewritten as:

$$-2\pi r\beta \frac{dh(t)}{dt} = \rho g h(t) \tag{7}$$

and the analytical solution of Eq. (7) is given by

$$h(t) = C_1 e^{-\frac{\rho g t}{2\beta\pi r}} \tag{8}$$

Furthermore, the hydraulic conductivity (permeability) k could be defined as:

$$k = \frac{h(t)}{t} \tag{9}$$

In this case, when $t = 1$; $k = h(t)$. With this in mind, Eq. (8) can be expressed as:

$$k = C_1 e^{-\frac{\rho g}{2\beta\pi r}} \tag{10}$$

Besides, as a second hypothesis, a linear relationship has been assumed between the air void content and the pore radius where the water can flow [21]. For this reason, the air void content can be expressed as:

$$A_{vc} = rC_2 \tag{11}$$

where A_{vc} is the air void content and C_2 a proportionality constant.

If Eq. (11) is substituted in Eq. (10), k will be

$$k = C_1 e^{-\frac{C_2\rho g}{2\beta\pi A_{vc}}} \tag{12}$$

Taking natural logarithms of both sides of the equation,

$$ln(k) = -\frac{C_2 \rho g}{2\beta\pi}\frac{1}{A_{vc}} + lnC_1 \tag{13}$$

and simplifying lnC_1,

$$lnC_1 = C_3 \tag{14}$$

Eq. (13) will appear as

$$ln(k) = -\frac{C_2 \rho g}{2\beta\pi}\frac{1}{A_{vc}} + C_3 \tag{15}$$

and which comes to represents the evolution of the hydraulic conductivity with the air void content. Finally, the limit of the right term of the equation, when the air void content tends to 0 is:

$$\lim_{A_{vc}\to 0} = \left(-\frac{C_2 \rho g}{2\beta\pi}\frac{1}{A_{vc}} + C_3\right) = -\infty \tag{16}$$

which coincides with the limit of the left term of the equation when the hydraulic conductivity tends to 0:

$$\lim_{k\to 0} = ln(k) = -\infty \tag{17}$$

Results and Discussion

Water Flow through Asphalt Mixture

Fig. 3 shows the hydraulic conductivity versus the air void content of the asphalt mixtures tested. These results have been obtained by means of the triaxial cell (dense and semidense mixtures) and falling head permeameter (discontinuous and porous mixtures) methods. From this Figure, it can be seen how the hydraulic conductivity increases with the air void content. It can also be seen that results obtained from either method present the same tendency, see colored area in Fig. 3. Moreover, Table 3 shows the statistical results of the hydraulic conductivity data after being adjusted to its respective probability distribution. Therefore, in Fig. 3 it can be observed that the hydraulic conductivity of dense and semidense asphalt mixtures was very low when compared to the hydraulic conductivity of discontinuous and porous asphalt mixtures. As it can be seen in Table 3, dense and semidense asphalt mixtures showed a

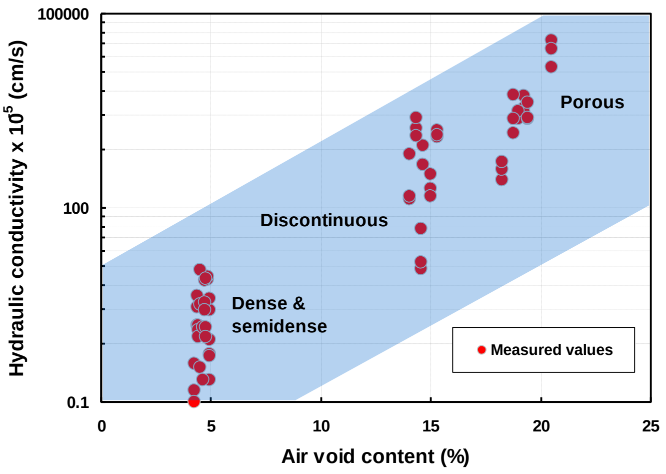

Fig. 3. Hydraulic Conductivity Versus Air Void Content of the Asphalt Mixtures Evaluated.

minimum and maximum hydraulic conductivity values between 1.9×10^{-7} and 1.1×10^{-4} cm/s respectively, while he hydraulic conductivity values of discontinuous and porous mixtures ranged between 1.2×10^{-4} and 3.8×10^{-1} cm/s. In addition, the average hydraulic conductivity of all asphalt mixtures analyzed ranged from 5.2×10^{-6} to 3.0×10^{-1} cm/s, showing similar values to those found in the literature (see Table 1).

To illustrate this, Fig. 4 shows the schematic relationship between the hydraulic conductivity and the air void content of (1) porous, (2) discontinuous, (3) semidense and (4) dense asphalt mixtures. The hydraulic conductivity and water flow capacity of asphalt mixtures increase with the increase of the air void content. In this way, the hydraulic conductivity is insignificant at low air void content (lower than 7%), but for higher values of air void content (more than 12%) the hydraulic conductivity increases rapidly. This happens because asphalt mixtures with an air void content lower than 7% presents a very high tortuosity [27], which hinders the passage of water through material. However, in asphalt mixtures with higher air void content (greater than 12%) the tortuosity level is reduced, presenting the material a higher capacity of drainage (see Fig. 4). The tortuosity is generally associated with the interconnection of the voids in the structure of the material.

Model Fit to Data

In Fig. 5, the probability-probability plot adjusted to a log-normal distribution function of two parameters, for the hydraulic conductivity data of the asphalt mixtures tested (dense, semidense,

Table 3. Statistical Results of Vertical Hydraulic Conductivity Measurements.

Asphalt Mixtures	Hydraulic Conductivity (cm/s)				Drainage Description
	Average	St Dev[a]	Min	Max	According to Table 1
Dense	5.2×10^{-6}	0.134	1.9×10^{-7}	8.5×10^{-5}	Very Low Permeability (V_L)
Semidense	1.4×10^{-5}	0.312	2.2×10^{-6}	1.1×10^{-4}	Low Permeability (L_P)
Discontinuous	3.3×10^{-3}	0.201	1.2×10^{-4}	2.5×10^{-2}	Permeable to Draining (P)
Porous	3.0×10^{-2}	0.271	2.6×10^{-3}	3.8×10^{-1}	Moderate Free Draining (M_F)

[a]St Dev: Standard Deviation.

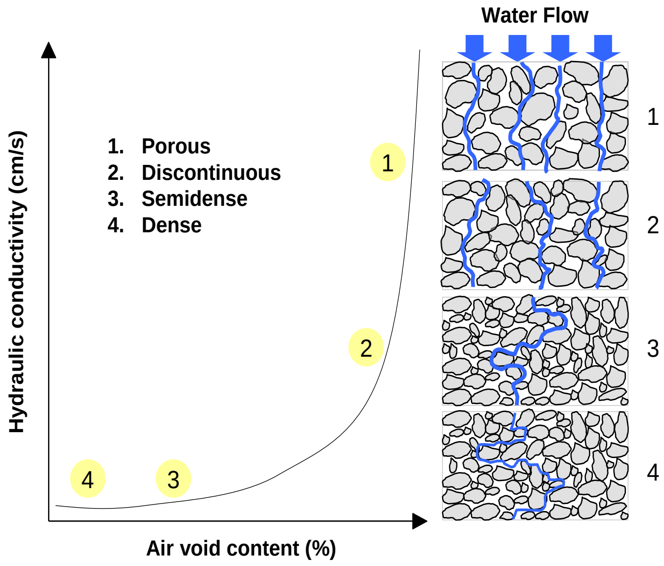

Fig. 4. Schematic Relationship between Hydraulic Conductivity and Air Void Content in Asphalt Mixtures with Different Pore Structure.

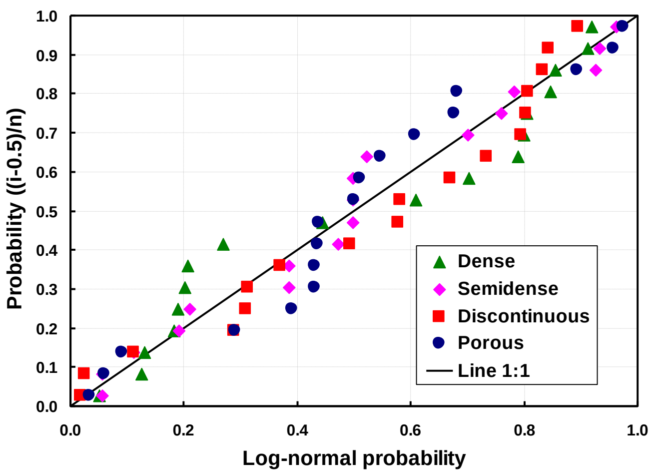

Fig. 5. Probability-probability Plot for the Hydraulic Conductivity Data of all Asphalt Mixtures Tested.

discontinuous, and porous), has been represented. A log-normal distribution has been used in this study considering that the water flow through saturated asphalt mixture can be modelled as a stochastic process. The reason is that the water flow is a random process that depends on a discrete time. This point is confirmed in the P-P plot of Fig. 5, where it can be observed that all the values can be aligned in a 1:1 straight line, with a minor data scatter.

In this way, in Fig. 6, the natural logarithm of the hydraulic conductivity data showed in Fig. 3 versus the inverse of the air void content have been fitted, through analytical approach model in Eq. (15) by using the 50% confidence curve. Additionally, in this Figure, the 5% and 95% confidence bands have been represented. Besides, in order to check the model fit presented in Eq. (14) to data, literature data from Table 1, collected from field and laboratory experiments, plus hydraulic conductivity data recommended in the European Standard [26], have been represented in this Figure. From this Figure, it can be observed that both the measured values and the

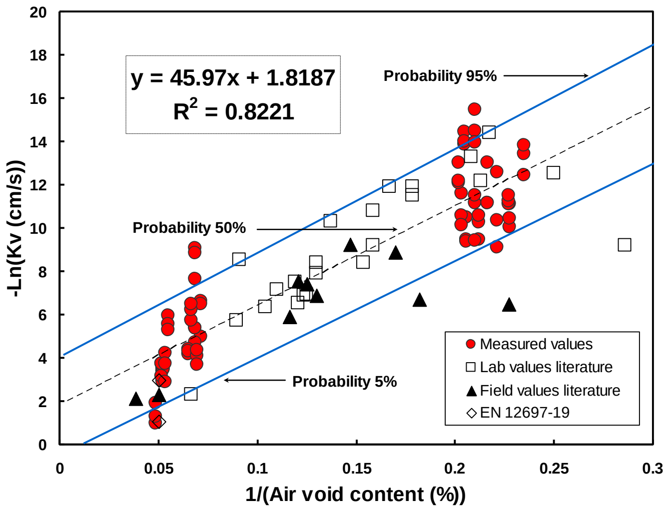

Fig. 6. Negative Logarithm of the Hydraulic Conductivity of Measured and Literature Values Versus Inverse of the Air Void Content.

literature data fit well to the proposed model, being most of the values between the 5 % and 95 % confidence bands. Additionally, it can be observed that most of the literature data obtained from field tests fall below the 50% confidence curve. The reason for this is that these materials may have suffered some damage over time and, for this, the tortuosity level changed [11-13]. Different factors that can affect the hydraulic conductivity are cracks produced during compaction or due to the traffic load, clogging by soil particles, which close the air voids thus reducing the total porosity of the mixture, and ageing of the materials. As a conclusion, it can be said that the model proposed in Eq. (15) offers a good fit (coefficient of determination 0.8221) of the hydraulic conductivity data for a wide range of air void content. In this way and based on the equation form (15), a general equation for the hydraulic conductivity of asphalt mixtures as a function of its air void content can be expressed as:

$$-ln(k) = 45.97\frac{1}{A_{vc}} + 1.82 \tag{18}$$

where A_{vc} is the air void content of the asphalt mixture, in %.

However, to apply this Equation, the air void content should be between 0% and 30%, which corresponds to the range of air void content for functional asphalt mixture. As a conclusion, Eq. (18) can be considered as a valid model to predict the vertical hydraulic conductivity of new asphalt concrete pavement, knowing its air void content. Moreover, the negative sign in the Eq. (18) may be attributed to that the theoretical model showed in the theoretical framework section was deduced under capillary flow through saturated asphalt mixture, while actually, water infiltration should have the opposite sign from the theoretical capillary flow. Additionally, this equation can be used to compare the hydraulic conductivity values estimated by different laboratory and field methods. Therefore, this equation can be used to predict the saturated hydraulic conductivity of asphalt mixtures with different porosity and test methods.

Conclusions

In this paper, the hydraulic conductivity (permeability) of asphalt mixtures with different air void content has been measured. With this objective, a new model to predict the hydraulic conductivity of asphalt mixtures based on its air void content has been developed. Additionally, the model has been verified through experimental and relevant literature data, presenting a good fit to data.

The new model developed in this paper provides an estimation of the hydraulic conductivity of asphalt mixture for the entire air void content spectrum where this material is functional: from 0 to 30%. This model has been developed through a modification of the Lucas-Washburn equation based in the capillary flow in porous materials, and verified through experimental and relevant literature data according to confidence bands established. From all these results, a general Eq. (18) that relates the hydraulic conductivity of asphalt mixture in relation to air void content has been obtained.

It has been observed that this equation is valid for new asphalt mixture. But that when asphalt mixture has been some time on site the hydraulic conductivity measurements deviate from the 50% probability curve. This happens because the asphalt concrete pavement can be affected by cracking and rutting due to traffic loads or by clogging by soil particles. Additionally, the negative sign in the equation may be attributed to that the theoretical model was deduced under capillary flow through saturated asphalt mixture, while actually, water infiltration should have the opposite sign from the theoretical capillary flow.

Moreover, in this paper, different average values for the hydraulic conductivity of dense, semidense, discontinuous and porous asphalt mixtures have been proposed in this study. Thus, it is suggested that these results may be employed as reference values for the vertical hydraulic conductivity of asphalt mixtures used in road pavements construction. Additionally, to measure the hydraulic conductivities of asphalt mixture two different methods, the triaxial cell for impervious mixtures and falling head permeameter for pervious mixtures, have been used. In both cases, the new model developed shows a very good correlation, so it can be concluded that both methods are suitable to evaluate the hydraulic conductivity of asphalt mixtures. Therefore, the new model developed in this study, can be used to predict the saturated hydraulic conductivity of asphalt mixtures with different porosity and test methods.

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