Discussions and Closures

ISSN 1997-1400 Int. J. Pavement Res. Technol. 7(3):225-226

Closure to "A New Model on the Hydraulic Conductivity of Asphalt Mixtures" by J. Norambuena-Contreras, E. Asanza Izquierdo, D. Castro-Fresno, Manfred N. Partl and Alvaro Garcia

Original paper published in Vol. 6, No. 5, pp. 488-495 (September 2013); **DOI**: 10.6135/ijprt.org.tw/2013.6(5).488

José Norambuena-Contreras[1] and Alvaro Garcia[2]

[1] Department of Civil and Environmental Engineering, University of Bío-Bío, Avda. Collao 1202, Concepción, Chile.
Email: norambuenaje@gmail.com

[2] University of Nottingham, Div. of Infrastructure and Geomatics, Faculty of Engineering, University Park, Nottingham NG7 2RD, United Kingdom.
Email: alvaro.garcia@nottingham.ac.uk

DOI: 10.6135/ijprt.org.tw/2014.7(3).225

Vardanega has presented a discussion of the paper by Norambuena-Contreras et al [1] on the mathematical form of the hydraulic conductivity of asphalt mixture, on the influence of gradation on the hydraulic conductivity of asphalt mixture, and on the air void connectivity of compacted asphalt mixtures. His arguments are based on semi-analytical equations from previous research works, such as Carrier [2] and Masad et al [3, 4]. Norambuena-Contreras and Garcia argue that these previous semi-analytical equations do not explain the water flow through asphalt mixture with a wide range of air void contents (A_{VC}).

Form of Mathematical Relationship

Kozeny-Carman equation is one of the commonly used equations to estimate the hydraulic conductivity of porous media [2]. The derivation of this equation is based on the assumption that the pore structure of a material can be represented by capillary tubes and the hydraulic radius theory applies [5]. The equation is valid only for laminar flow [6]. According to Kutay [5], the Kozeny-Carman equation does not apply to asphalt mixtures with hydraulic conductivities less than 1×10^{-1} cm/s. This hydraulic conductivity is obtained in mixtures with air void content higher than approximately 25% [1], which is unrealistic for asphalt mixture.

In Norambuena-Contreras et al [1] it is stated that the forces affecting the water flow through saturated asphalt mixture are the surface tension, the liquid inertia, the water weight and the friction of water against the walls of the asphalt mixture pores. This is equivalent to the movement of bitumen through a crack in asphalt concrete [7]. Depending on the size of pores and on their connectivity, these forces will change their influence on the water flow through asphalt mixture.

In Table 4, different equations representing hydraulic conductivity versus air void content are shown. The exponential power and hyperbolic models are commonly used fitting equations. These three fitting models have not been deducted based on physical considerations.

Table 4. Various Models Relating Hydraulic Conductivity with Air Void Content.

Model Name	Author	Equation Form
Exponential Fitting Model	Cooley et al [8]	$k = a(e)^{b \cdot A_{VC}}$
Power Fitting Model	Kanitpong et al [9]	$k = a(A_{VC})^b$
Hyperbolic Fitting Model	Naatatmadja [10]	$k = \frac{a}{(1/A_{VC}) - b}$
Norambuena-Garcia Model	Norambuena-Contreras et al. [1]	$k = e^{-\left(\frac{a}{A_{VC}}+b\right)}$

A good hydraulic conductivity versus air void content algorithm should tend to 0 cm/s when the air void content of asphalt mixture is 0% and should tent to an asymptote when the air void content approaches to 100%. The reason for this is because air void content 100% represents an empty water conduit with the same diameter of the test specimen. Water cannot circulate faster than in this case. This allows us to discard immediately the Exponential and Power fitting models, because they do not tent to an asymptote. Moreover, the Hyperbolic fitting model [10] has not been deducted from any known factor affecting the water flow through asphalt mixture.

The Norambuena-Garcia model (see Table 4), proposed in Norambuena-Contreras et al [1], is the only existing algorithm that considers all the forces influencing the water flow through asphalt mixture. It presents a certain resemblance to the Hyperbolic fitting model shown in Naatatmadja [10] but it is not equivalent.

In addition, Fig. 7 shows the comparison of a simple power law and the Norambuena-Garcia model. Although the value of the coefficient of determination (R^2) is higher for the power law fitting (0.845) than for the Norambuena-Garcia model (0.822), both values cannot be compared because the power law measures the variation of hydraulic conductivity, explained by air void content, while the Norambuena-Garcia model measures the variation of the logarithm of hydraulic conductivity, explained by air void content. R^2 can be used only to compare similar variables with the same fitting model (e.g. Garcia et al [11] and Norambuena-Contreras [12]).

Gradation Influence and Air Void Connectivity

In Fig. 5, a P-P plot of the hydraulic conductivity data for all the mixtures tested is shown. In this figure, a log-normal probability distribution has been used. The reason for this is because water flow through asphalt mixture is a stochastic process: Consider a thin section of asphalt mixture, of differential width, dh, with air void content, e_1.Water will circulate through this section at a speed, dh/dt

(see Eq. (9)). The water speed is equivalent to the hydraulic conductivity of the thin section, and equal to k_1. The water speed at the beginning of the next thin section will be k_1. If the hydraulic conductivity value of the second section is k_2, the total combined hydraulic conductivity of both sections (k) will be $k = k_1 \times k_2$.

This means that the hydraulic conductivity of asphalt mixture test samples with equivalent air void content will have a logarithmic distribution. For this reason, only the logarithm of the hydraulic conductivities can be compared.

References

1. Norambuena-Contreras, J., Izquierdo, E.A., Castro-Fresno, D., Partl, M.N., and Garcia, A. (2013). A New Model on the Hydraulic Conductivity of Asphalt Mixtures. *International Journal of Pavement Research & Technology*. 6(5), pp. 488-495.
2. Carrier, W.D. III. (2003). Goodbye Hazen: Hello, Kozeny-Carman. *Journal of Geotechnical and Geoenvironmental Engineering*, 129(11), pp. 1054-1056.
3. Masad, E., Birgisson, B., Al-Omari, A., and Cooley, A. (2004). Analytical derivation of permeability and numerical simulation of fluid flow in hot mix asphalt. *Journal of Materials in Civil Engineering*, 16(5), pp. 487-496.
4. Masad, E., Al-Omari, A., and Lytton, R. (2006). Simple method for predicting laboratory and field permeability of hot mix asphalt. *Transportation Research Record*, No. 1970, pp. 55-63.
5. Kutay, M. E. (2005). Modeling Moisture Transport in Asphalt Pavements. Ph.D. Thesis, University of Maryland, USA.
6. Vardanega, P.J. (2014). State of the Art: Permeability of Asphalt Concrete. *Journal of Materials in Civil Engineering*, 26(1), pp. 54-64.
7. García, A., Pacheco-Bueno, M., Norambuena-Contreras, J., Partl, M.N. (2013). Induction healing of dense asphalt concrete. *Construction and Building Materials*, 49, pp. 1-7.
8. Cooley, L.A., Jr., Brown, E.R., and Maghsoodloo, S. (2001). Development of critical field permeability and pavement density values for coarse-graded Superpave pavements. NCAT Report 01-03, National Centre for Asphalt Technology, Auburn University, Auburn, AL, USA.
9. Kanitpong, K., Benson, C. H., and Bahia, H. U. (2001). Hydraulic conductivity (permeability) of laboratory-compacted asphalt mixtures. *Transportation Research Record*, No. 1767, pp. 25–32.
10. Nataatmadja, A. (2010). The use of the hyperbolic function for predicting critical permeability of asphalt. *Proceedings 24th ARRB Conference – Building on 50 years of road and transport research* (CD-ROM), ARRB Group, Melbourne, Victoria, Australia.
11. García, A., Norambuena-Contreras, J., and Partl, M.N. (2013). A parametric study on the influence of steel wool fibers in dense asphalt concrete. *Materials and Structures*, doi: 10.1617/s11527-013-0135-0.
12. Norambuena-Contreras, J. (2013). Hydraulic and Mechanical Behaviour of Materials Used in Road Pavement Construction. Ph.D. Thesis, University of Cantabria, Spain.