Journal of Civil Engineering and Architecture 17 (2023) 621-629
doi: 10.17265/1934-7359/2023.12.003

# A Full Simulation Study for the Design Optimization of Open-Graded Pavement

Andrea Umiliaco
*Department of Sciences of Civil Engineering, University of Roma, Roma 00185, Italy*

**Abstract:** Water trapped within the HMA (Hot Mix Asphalt) layers of a flexible pavement causes the loss of strength and durability of the material producing surface damages and deteriorations such as stripping and ravelling. Open-graded pavements are considered potentially to be effective solutions to avoid these forms of infiltration-related distress. The main property that influences the performance of HMA is the hydraulic permeability. The permeability is a function of several properties of HMA which make the process of mix design very complex and uncertain. In this paper, starting from different grading curves, we evaluate the dependence of the permeability by the size distribution of aggregates using a full numerical model that has yet been validated through experimental tests and theoretical calculations. The correlation between the grain size distributions and the hydraulic permeability is very useful in order to simplify and optimize the design of open-graded pavements.

**Key words:** Simulation, design optimization, pavement.

## 1. Introduction

The presence of water in asphalt mixtures causes lots of adverse effects on flexible pavement and reduces its performance. Moisture related damage in asphalt pavements, that consists in the loss of strength and durability in HMA (Hot Mix Asphalt) caused by the presence of water, is global concern. This kind of damage is induced by the loss of bond between aggregate and binder surface (adhesive failure) and loss of bond within the binder itself (cohesive failure). These two modes of failure occur in asphalt pavements as loss of binder (stripping), loss of aggregate (ravelling), cracking and even permanent deformation. Open-graded pavements are considered potentially to be effective solutions to avoid the infiltration related distress. These asphalt mixes with high degrees of porosity (open-graded mixes) drain significantly better than normal pavement materials presenting a high value of the index of the voids and hydraulic interconnection among them. Early applications of porous pavement were investigated by Thelen et al. [1] and Diniz [2], but these studies were generally limited to parking lots and driveways. Gemayel and Mamlouk [3] presented a study (sponsored by the Arizona DOT), which investigated several engineering properties of open-graded friction course. They found that the tensile strength and resilient modulus of open-graded mixes were about half of the value of normal dense-graded asphalt. Furthermore, the open-graded material was extremely sensitive to temperature. At high temperatures, these materials exhibited significant decreases in resilient modulus and stability. Additional studies about strength of open-graded mixes were limited to emulsion mixtures by Hicks et al. [4] and asphalt stabilized aggregate bases by Majidzadeh and Elmitiny [5]. Qi et al. [6] presented some new research on the development of more durable asphalt binder through the use of polymer modifiers. Preliminary research into drainage and flow in porous pavements was also made by Isenring et al. [7]. A recent survey made by Kandhal and Mallick [8] points out that the design and construction play a key role in determining the performance of open-graded asphalt

**Corresponding author:** Andrea Umiliaco, research fields:.road safety, numerical modeling.

pavements. All these studies show that one of the main challenge in designing an open-graded pavement, that affects its durability and its safety, is determining a reasonable compromise between mechanical and hydraulic characteristics of open-graded mixtures. They depend on the road materials and mix design as on how the pavement is developed. Traditionally a conceptual/empirical approach, physically based, is followed to identify materials requirements and construction standards. Conceptual models are generally approximated and, consequently, laboratory tests on the mixes or measurements on the real scale are performed to check the final characteristics of pavement. More in depth, this approach is mostly effective if the design objective is univocal, but if the mixture must respect different and concurrent requirements as mechanical and hydraulic standards the approach is not of great effectiveness [9]. In particular, the case of hydraulic and mechanical properties of mixes is very intriguing because two different objectives are concurrent. In fact an adequate hydraulic permeability is possible if the voids content is high and the voids system is open [10, 11]. On the contrary the mechanical characteristics depend on cohesion and friction among aggregates and low levels of voids content are required. The mix design appears in this case as an optimization problem. However, because there are no analytical nor empirical models available, it often happens that the mixture is designed adopting a minimum standard for mechanical characteristics and the hydraulic permeability is overestimated. This oversize produces many disadvantages and problems from an economic and environmental point of view [12]. It is very difficult to solve this optimization problem. In fact, while the mechanical properties can be investigated through standardized laboratory measurements, the traditional approach used to evaluate the expected drainage capability of pavement is controversial. It is based on laboratory tests using hydraulic parameters [13] or measures on the field, and it is unable to reach a correct estimation of permeability due to many approximations in measurements and to the wide variety of devices, that work under different conditions and measuring different parameters. In order to solve these problems in the last years numerous researchers have attempted to calculate permeability through novel theoretical models [14]. These models are categorized as analytical, that consider the permeability as a function of porosity and of the average particles size; probabilistic, that employ simplified assumptions on the probabilistic distribution of air voids and their interconnection; morphological, that simulate the microscopic geometry of mixes through the construction of equivalent material to simulate HMA; and numerical, that calculate the permeability by solving fluid flow equations numerically. In this paper, in order to overcome the points of weakness shown by permeability models, we propose a novel full numerical method based on simulation of unsteady-flow of water within open-graded mixture. This method can be considered an integration of the models based on numerical and morphological analysis. In particular this novel approach reduces computational complexity of the full morphological models and increases the reliability of numerical models. The model integrates two modules, one for the generation of the physical micro-structure of the mixture from the design inputs and one simulating the fluid flow in open-graded mixes basing on the LB (Lattice-Boltzmann) method. This mathematical approach allows predicting pavement permeability in order to find a valid procedure to support and to optimize the mix design. The reliability of the results has been yet validated through experimental tests and theoretical calculations [15, 16].

## 2. Factors Affecting Permeability of HMA

Permeability of porous media is defined as the ability to transmit fluids through the voids of the porous material when it is subjected to different hydraulic loads. Hydraulic conductivity is numerically defined by

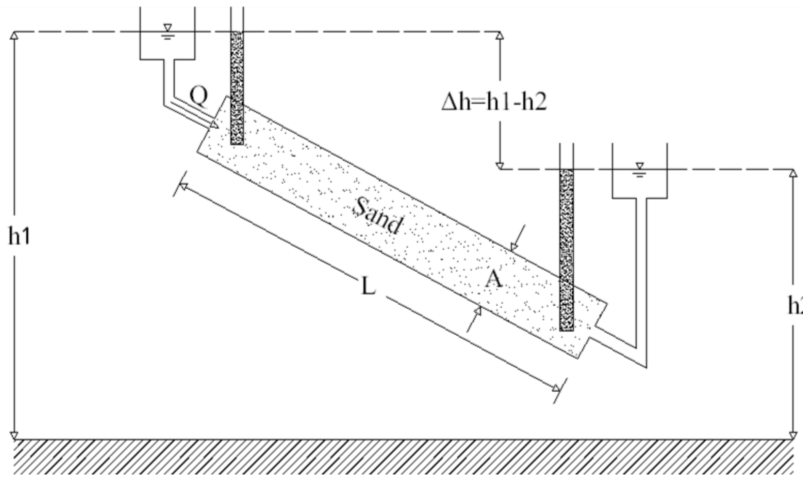


**Fig. 1 Darcy's apparatus.**

Darcy's Law, derived from the Darcy's experiments (Fig. 1), which states that the fluid discharge velocity is directly proportional to the hydraulic gradient [17]. It can also be considered as the flow rate (*Q*), in units of volume, passing through a cross-sectional area of the porous medium in unit time, under the influence of a pressure gradient (*i*).

Darcy's law depends on the flow condition and it is expressed in the following form:

$$Q = KiA \quad (1)$$

where, *K* is the proportional factor called hydraulic conductivity (or permeability coefficient), *Q* is the flow rate in unit of volume, *A* is the cross-sectional area, *i* is the hydraulic or pressure gradient, defined as the pressure difference ($\Delta h$) divided by the length of the hydraulic path (*L*). The flow rate divided by the cross-sectional area represents the average velocity of the fluid flow (*v*). Permeability coefficient (*K*) is expressed in velocity units for a given hydraulic head.

Darcy's law, applied to a porous medium, is valid when the fluid travels at a very low speed and no turbulence occurs, more in depth the classification of fluid flow into steady, transient, or turbulent flow depending on the variability of flow velocity in time or direction. Fluid flow in porous media is driven by two different mechanisms. The first one is known as the creeping flow, which is due to the fluid viscosity. The second one is convection flow, which is due to the inertial forces. The significance of either one of these terms depends on the value of the modified Reynolds number (Re*), which combines fluid density ($\rho$), viscosity ($\mu$), velocity of flow (*v*), and a characteristic dimension of the particles of porous media (*D*) [18]. It is expressed in the following form:

$$\mathrm{Re}* = \frac{vD\rho}{\mu} \quad (2)$$

For the same fluid and porous material, the velocity changes as a function of the applied pressure gradient in the direction of the flow as illustrated in Fig. 2. The linear part of the curve represents the region of small Re* where creeping flow is the dominant mechanism.

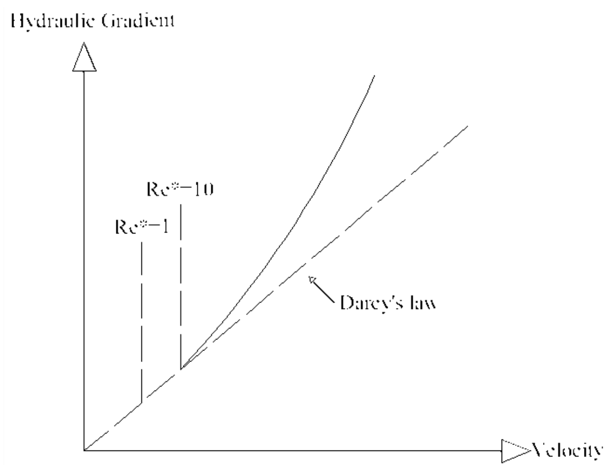


**Fig. 2 Schematic curve relating hydraulic gradient and velocity.**

Since fluid flow in porous materials is considered as laminar flow, then, permeability of most porous materials is usually calculated assuming small Re* in the linear range of the curve shown in Fig. 2. This assumption has been verified in numerical simulations of fluid flow in the internal structure of porous media such as sandstone, cement paste, and sands [19, 20]. Scheidegger [18], therefore, showed that permeability of porous materials depends on the properties of the porous material and the fluid, following this expression:

$$K = k\frac{\gamma}{\mu} \tag{3}$$

where $k$ is a component of the absolute permeability tensor; $K$ is the Darcy's permeability coefficient, as defined previously, $\gamma$ is the unit weight of the fluid and $\mu$ is the viscosity of the fluid.

The properties of the porous material are represented by the absolute permeability ($K$) which is a function of the porous material only. The properties of the fluid are represented, on the other hand, by its unit weight and viscosity. Permeability will be affected by any changes in their properties. The viscosity and the unit weight of the fluid are mainly affected by temperature. The porous material, on the other hand, is changing whenever the properties of its constituents (aggregates, asphalts and air voids) change.

Several studies have shown that the permeability of asphalt mixes is a function of percent air voids, size and number of air voids, aggregate gradation, aggregate shape, specimen thickness, and compaction procedures, but it is very difficult to find a reliable correlation between these characteristics and the hydraulic conductivity. In fact while Brown et al. [21] show that the dense-graded pavements become too permeable for percentage of voids above 8%, Choubane et al. [22] indicated that coarse-graded superpave mixes could be excessively permeable to water at in-place air voids less than 8%.

In order to overcome these problems, in this paper we try to find a method to determine the drainage capacity and to solve the optimization problem of mix design, evaluating the dependence of the permeability by the size distribution of aggregates using a full numerical model.

## 3. The Simulation Model

The novel full numerical method, used in this work, consists of two different models, that are integrated in a cascade.

The first is based on the characterization of the microscopic structure of the sample. In particular this model allows defining the parameters that identify the distribution and the position of the constituents (aggregates, bitumen and air voids) of the open-graded mixes. In order to define these parameters the model uses the RSA (random sequential adsorption) for the numerical generation of the sample. The RSA procedures are logical randomly placed algorithms which add, starting from mix-design inputs, the particles, that represent a fixed distribution of aggregate size, in a specific domain. The positioning of these particle, considered as spheres, is achieved by verifying that the volume occupied by the object that the algorithm has to insert does not overlap with the previously added elements [23].

In Fig. 3 an example of the output of the numerical generation in a two dimensional domain is shown.

The second model is used to simulate the flow of water inside the asphalt sample. It is based on LB method. The LB method is a class of CFD (computational fluid dynamics) methods for fluid simulation, it has evolved from the theory of LGA (Lattice Gas Automata) [24]. Among

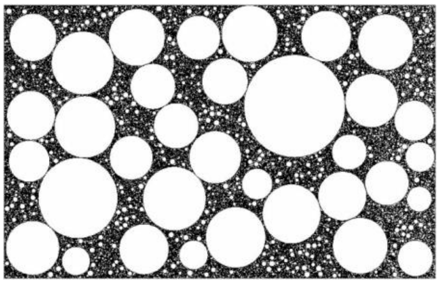

**Fig. 3 RSA 2D output.**

various techniques, the LB method is widely accepted. It has proven to be extremely efficient in the simulation of fluid flow through the complex geometries due to the facility of implementing boundary conditions and to the numerical stability in a wide variety of flow conditions. The LB method approximates the continuous Boltzmann equation by discretizing a physical space with lattice nodes and a velocity space by a set of microscopic velocity vectors [25]. The lattice nodes are uniformly spaced in order to represent the voids and the solids, while the discrete set of microscopic velocities is defined for propagation of fluid molecules (Fig. 4). For each node of the lattice the macroscopic flow properties, density and velocity, can be calculated.

The reliability of the model is already validated using experimental tests and theoretical calculation [15, 16]. In particular starting from the generation of the synthetical sample and the subsequent simulation of the flow of water, as described previously, it is possible to determine a fundamental property related to the permeability: tortuosity. The tortuosity of a porous medium describes network complexity in porous media (flow paths). It depends on various parameters of the particles and settlement: the shape, size, and type of the grains, pores, and pore channels; mode of packing of the grains; grain size distribution; the orientation; and nonuniformity of the grains and it is defined as:

$$T = \frac{L_e}{L} \tag{4}$$

where $L$ is the minimal geometrical distance between inlet and outlet and $L_e$ is an average effective hydraulic path length, of course it results $L_e > L$.

The knowledge of this parameter through the simulation model, introduced in most of permeability models, allows evaluating the permeability according to the following equation:

$$K = \frac{\gamma}{\mu}\frac{n_e^3}{bT^2}\frac{1}{S_a^2} \tag{5}$$

where $K$ is the hydraulic conductivity, $S_a$ is the specific surface area, $n_e$ is the effective porosity, $\gamma$ is the unit weight of the fluid (water at 20 ℃), and $\mu$ is fluid viscosity, $b$ is a constant given as 2 for perfectly circular pore structure and 3 for rough texture on the pore surface.

In previous works, the reliability of the results, obtained from the simulation and from the theoretical approach, was already validated by the comparison with some experimental outcomes, coming from laboratory tests using a hydraulic parameter.

Fig. 5 shows the correlation between the values of $K$ measured and $K$ predicted of two grading curves, from basaltic and silica-limestone aggregates, and three different percentage of bitumen for each of the four Marshall samples, for a total of 24 tests. The range of $K$ values accepted for open-graded asphalt pavements is 0.02-0.05 cm/s and the range of $T$ values accepted is 1.1-1.4.

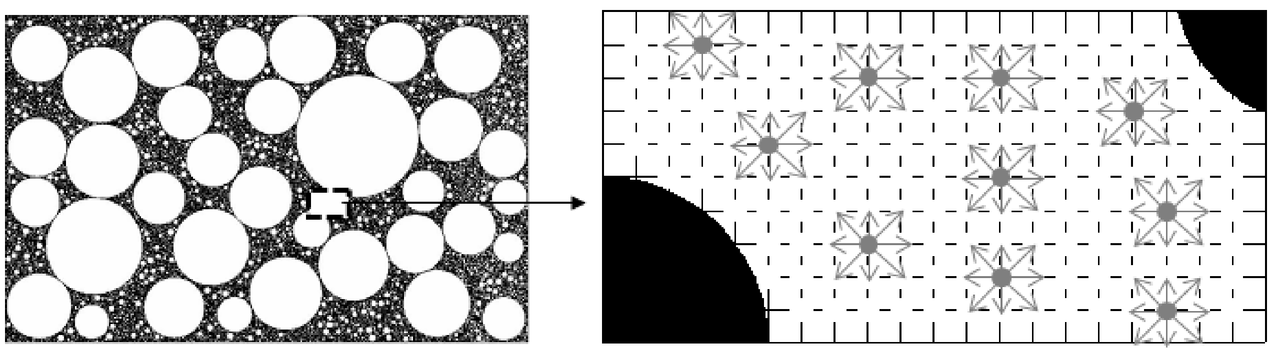

**Fig. 4 LB grid.**

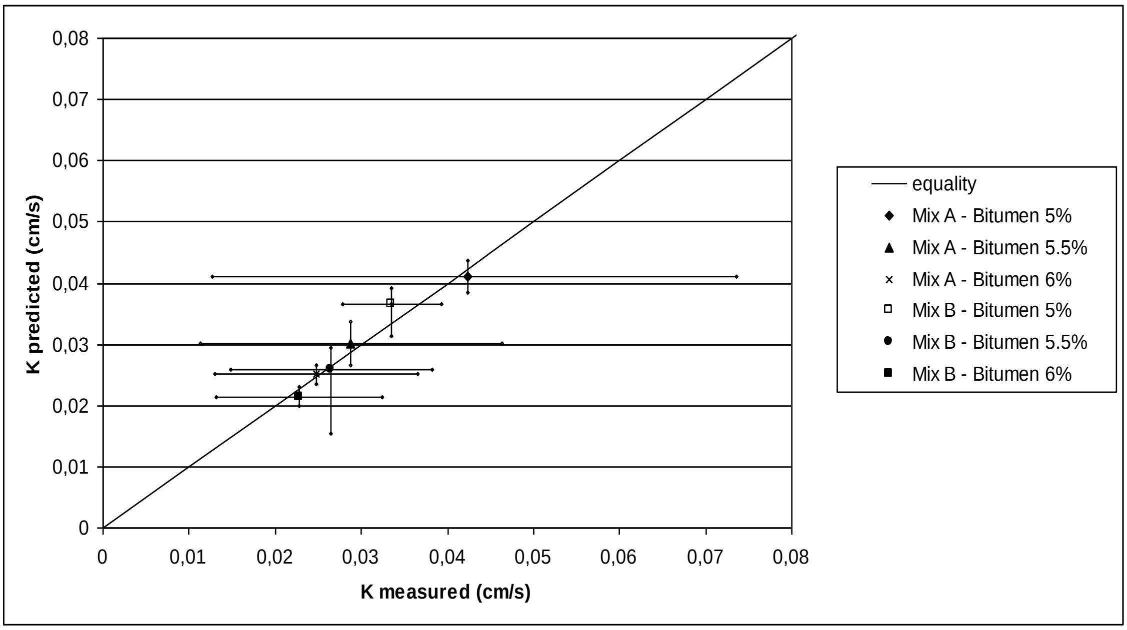


**Fig. 5 Validation of the model.**

## 4. The Application

In order to investigate a possible correlation between hydraulic permeability and the grain size distribution, starting from five grading curves we evaluate the drainage capability of the mixes coming from these grading curves using the simulation model. In particular a fixed distribution of aggregates size of open-graded mixes has been selected according to the volumetric standard of the Superpave mixture design (U.S. Department of Transportation).

Starting from this initial grading, we have considered an area obtained by changing the percentages of passing by ±10% (Fig. 6). Within this area four other grading curves have been selected. The physical characteristics of samples are summarized in Table 1. It is assumed a bitumen percentage for the mixture equal to 5%.

In Table 2, it also shows the diameter of the sieve corresponding to 50% passing ($D_{50}$). This parameter plays an important role regarding the aggregate grading.

The hydraulic permeability of the 5 mixes has been simulated through the full numerical model.

In particular for each of the synthetical samples the model simulates the different flow paths of the water, as shown in Fig. 6. The flow paths geometries allow calculating the tortuosity (4) by tracking a band of most probable water paths and by assuming an average trajectory to measure the length of the paths.

**Table 1 Gradings of the samples.**

| Sieve size (mm) | % Passing Sample 1 | % Passing Sample 2 | % Passing Sample 3 | % Passing Sample 4 | % Passing Sample 5 |
|---|---|---|---|---|---|
| 25 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 15 | 90.0 | 94.5 | 99.2 | 85.5 | 81.2 |
| 10 | 72.0 | 75.6 | 79.4 | 68.4 | 65.0 |
| 5 | 43.0 | 45.2 | 47.4 | 40.9 | 38.8 |
| 2 | 23.0 | 24.2 | 25.4 | 21.9 | 20.8 |
| 0.4 | 10.0 | 10.5 | 11.0 | 9.5 | 9.0 |
| 0.18 | 7.0 | 7.4 | 7.7 | 6.7 | 6.3 |
| 0.075 | 5.8 | 6.1 | 6.4 | 5.5 | 5.2 |
| $D_{50}$ | 6.21 | 5.79 | 5.41 | 6.65 | 7.14 |

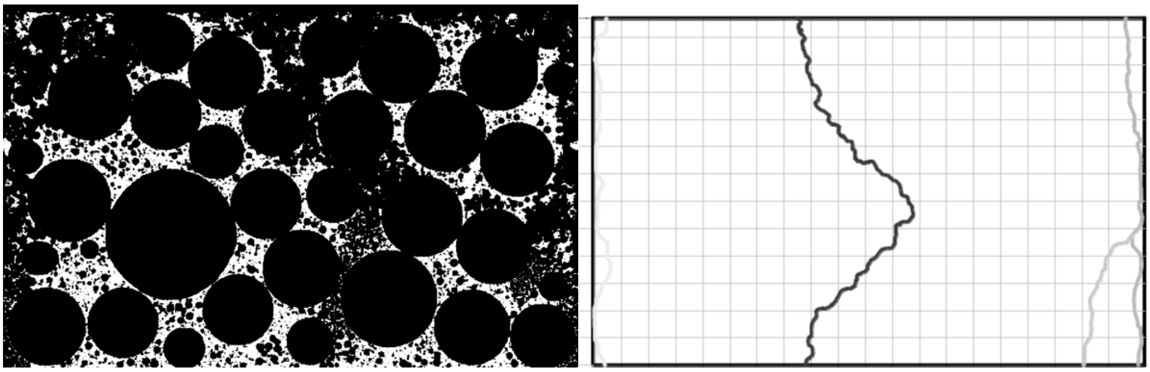

**Fig. 6 Reconstruction of the hydraulic path from LB simulation.**

**Table 2 Tortuosity and permeability versus $D_{50}$.**

| $D_{50}$ (mm) | 5.41 | 5.79 | 6.21 | 6.65 | 7.14 |
|---|---|---|---|---|---|
| $T$ | 1.226 | 1.231 | 1.209 | 1.176 | 1.183 |
| $K$ (cm/s) | 0.0181 | 0.0180 | 0.0186 | 0.0197 | 0.0195 |

Using Walsh and Brace Eq. (5), where the values of parameters are evaluated from output of numerical generation, we are able to calculate the hydraulic permeability for each simulated sample. The values of tortuosity and the related permeability for the virtual samples are shown in Table 2.

Fig. 7 correlates the hydraulic permeability ($K$), determined from the numerical method, with the diameter of the sieve corresponding to 50% passing ($D_{50}$). The figure shows that by increasing the dimension of aggregate, the permeability generally increases. This correlation, moreover, can be defined by a linear regression ($R^2$ = 0.9008):

$$K = \alpha D_{50} = 0.0107 D_{50} + 0.1209 \quad (6)$$

Fig. 8 correlates the tortuosity values ($T$), as defined in Eq. (4), with the diameter of the sieve corresponding to 50% passing ($D_{50}$). The figure shows that the expression which defines the best correlation between the two parameters (the highest value of $R^2$ = 0.8095) is parabolic. Moreover, the tortuosity values decrease as the square of the dimension of aggregate. The correlation, therefore, is defined by following expression:

$$T = gD_{50}^2 = 0.0029 D_{50}^2 - 0.0694 D_{50} + 1.5227 \quad (7)$$

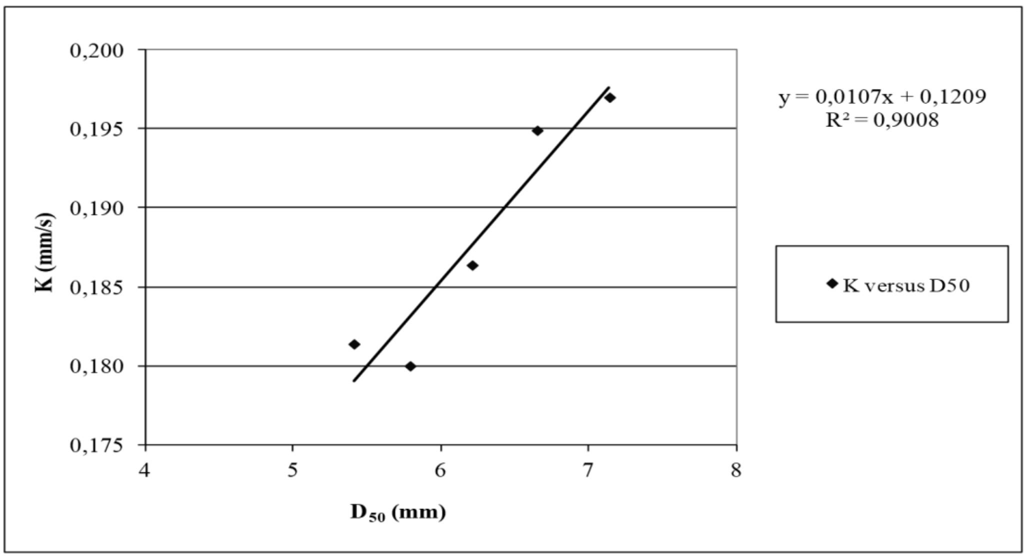


**Fig. 7 *K*-$D_{50}$ regression.**

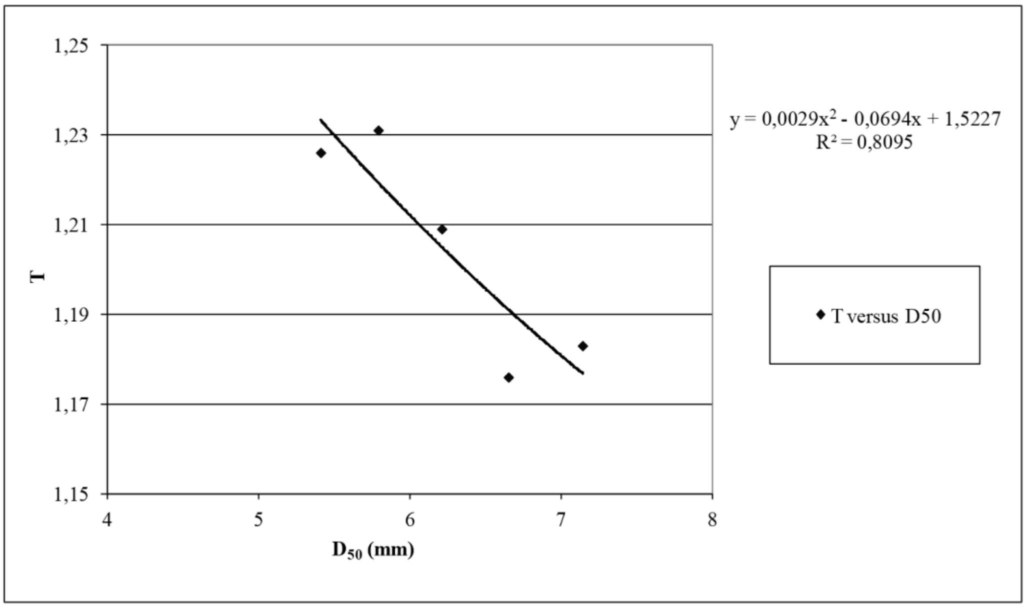


**Fig. 8 Tortuosity-$D_{50}$ regression.**

## 5. Conclusions

The presence of free water on the pavement surface contributes to reducing the load carrying capacity through promoting distresses such as moisture cohesive and adhesive damage, fatigue cracking, and permanent deformation. Under these conditions it is clear that understanding fluid drainage is very important also in design life of pavement. Traditionally the drainage capacity, is evaluated after pavement development generally through on site standardized tests. The final permeability is generally higher than needed. It induces relevant economic (cost of adequate aggregate, of modified bitumen, etc.) and environmental (not renewable resources consumption) over-costs. Analogously and simultaneously, the mechanical requirements have to be respected. As mentioned, such two needs are satisfied through the selection of specimens and the bitumen content. Consequently, the mix design problem has to be assumed to be a problem of optimization, where mechanical and hydraulic expectations imply contrasting requirements in terms of specimen selection and mix development. In order to solve this optimization problem, in this paper, a full numerical model is used to simulate the unsteady flow of water through an open-graded asphalt mix. This model allow evaluating the permeability by a full numerical procedure. The hydraulic permeability is influenced by main factors of a bituminous mix, as aggregate grading, bitumen and void percentages. Regarding the aggregate grading, in this paper, we evaluate the correlation between the grain size distribution and the drainage capacity, starting from different grading curves. The results show that it is possible to find a linear correlation between these two parameters. The outcomes are certainly very promising however additional experimental validations have to be carried out in the next future, in order to reach the needed reliability and a stable procedure.

## References

[1] Thelan, E., and Howe, L. 1978. *Porous Pavement*. Philadelphia: The Franklin Institute Press.

[2] Diniz, E. V. 1980. *Porous Pavement: Phase I, Design and Operational Criteria*. Washington, D.C.: Environmental Protection Agency, pp. 80-135.

[3] Gemayel, C. A., and Mamlouk, M. S. 1988. "Characterization of Hot-Mixed Open Graded Asphalt Mixtures." *Transportation Research Record* 1171: 184-92.

[4] Hicks, R. G., Gatch, D. R., Williamson, R., and Steward, J. 1979. "Open-Graded Emulsion Mixes for Use as Road Surfaces." *Transportation Research Record* 702: 64-72.

[5] Majidzadeh, K., and Elmitiny, R. 1981. *Development and Implementation of Pavement Drainage Design*

*Guideline in Ohio*. *Report FHWA/OH, 81/007*. Columbus: TRID.

[6] Qi, X., and Sebaaly P. E. 1995. "Evaluation of Polymer-Modified Asphalt Concrete Mixtures." *Journal of Materials in Civil Engineering* 7: 117-24.

[7] Isenring, T., Harald, K., and Scazziga, I. 1990. "Experience with Porous Asphalt in Switzerland." *Transportation Research Record* 1265: 41-53.

[8] Kandhal, P. S., and Mallick, R. B. 1998. *Open Graded Friction Course: State of the Practice*. *NCAT Report*. Auburn, A.L.: National Center for Asphalt Technology, pp. 98-7.

[9] Nukunya, B., Roque, R., Tia, M., and Birgisson, B. 2001. "Evaluation of VMA and Other Volumetric Properties as Criteria for the Design and Acceptance of Superpave Mixtures." *Proc. of AAPT* 70: 38-69.

[10] Cooley, L. A. Jr., Mallick, R. B., Teto, M. R., Bradbury, R. L., and Peabody, D. 2003. "An Evaluation of Factors Affecting Permeability of Superpave Designed Pavements." *NCAT Report* 2-3: 29.

[11] Masad, E. A. 2003. *Analysis of Permeability and Fluid Flow in HMA.* Washington, D.C.: Transportation Research Board.

[12] Benedetto, A. 2007. "Open Graded Asphalt Mixes: Permeability and Mechanical Characteristics." *International Journal of Pavement* 6: 63-74.

[13] Kanitpong, K., Benson, C. H., and Bahia, H. U. 2001. "Hydraulic Conductivity (Permeability) of Laboratory Compacted Asphalt Mixtures." *Transportation Research Record* 1767: 25-33.

[14] Al-Omari, A., and Masad, E. 2005. "Analysis of HMA Permeability through Microstructure Characterization and Simulation of Fluid Flow in X-Ray CT Images." In *Proceedings of the First Middle East International Conference on Advances in Civil, Mechanical, and Materials Engineering*, Amman, Jordan.

[15] Benedetto, A., and Umiliaco, A. 2012. "Evaluation of Hydraulic Permeability of Open-Graded Asphalt Mixes Using a Full Numerical Simulation." *Journal of Materials in Civil Engineering* 26 (4): 599-606.

[16] Benedetto, A., and Umiliaco, A. 2012. "Simulation of Unsteady Flow of Water in Open Graded Pavement." *International Journal for Numerical and Analytical Methods in Geomechanics*.

[17] Darcy, H. 1856. *Les fontaines publiques de la ville de Dijon.* Paris: Victor Dalmont. (in French)

[18] Scheidegger, E. 1974. *The Physics of Flow through Porous Media.* Toronto: Univ. of Toronto Press.

[19] Adler, P. M., Jacquin, C. G., and Quiblier, J. A. 1990. "Flow in Simulated Porous Media." *Internat. J. Multiphase Flow* 16 (4): 691-712.

[20] Martys, N. S., Torquato, S., and Bentz, D. P. 1994. "Universal Scaling of Fluid Permeability for Sphere Packings." *Physical Review* 50: 403-8.

[21] Brown, E. R., Collins, R., and Brownfield, J. A. 1989. "Investigation of Segregation of Asphalt Mixtures in the State of Georgia." *Transportation Research Record* 1217: 1-8.

[22] Choubane, B., Page, G., and Musselman, J. 1998. "Investigation of Water Permeability of Coarse Graded Superpave Pavements." *Journal of the Association of Asphalt Paving Technologists* 67: 254-76.

[23] Benedetto, A. 2009. "Numerical Simulation of Mechanical and Hydraulic Characteristics of Open Graded Mix." In *Proceedings of Conference on Maintenance and Rehabilitation of Pavements and Technical Control*, Torino, Italy.

[24] Von Neumann, J. 1940. "The Estimation of Probable Error from Successive Differences." *Aberdeen Proving Ground* 175: 19.

[25] Kutay, M. E., Aydilek, A. H., and Masad, E. 2006. "Laboratory Validation of Lattice Boltzmann Method for Modeling Pore-Scale Flow in Granular Materials." *Computers and Geotechnics* 33: 381-95.