AIR PERMEABILITY OF POROUS ASPHALT PAVEMENT

Giuliani F.
Associate Professor – University of Parma – felice.giuliani@unipr.it
Costa A.
Associate Researcher – University of Parma – arianna.costa@unipr.it

ABSTRACT

We propose the results of experimental analyses on the draining capability of asphalt pavement by quantifying the filtration process indicator and permeability coefficient, through the use of an original air permeameter. This apparatus exploits the physical properties of air, and can solve the problems of measuring methods using water, which often yield contradictory results and non-repeatable tests. Such device is specifically conceived for pavement applications and ensures both a simple, rapid testing system, and high reliability and repeatability of the measurement.

Keywords: porous asphalt, permeability, hydraulic conductivity.

1. BACKGROUND

1.1 Introduction

Rapid elimination of rainwater from road surfaces is a fundamental safety condition for vehicle traction, in particular during the braking phase. Asphalt pavements in porous mixture are studied to improve adhesion between tire and asphalt layer, by changing the superficial flow of water into filtration through a porous material.

The high efficacy of porous asphalt layers in the road pavement, even in the most adverse weather conditions, calls for measurement devices of the drainage properties by measuring hydraulic conductivity.

The actual conditions of water flow through a porous layer have been studied for several years and different measurement devices have been developed. Instruments are based on different hydraulic assumptions in the search for a simple valid method to quantify the permeability of porous asphalt in both the field and a laboratory setting. The instruments used in the field mostly consist in conventional apparatus for rapid assessment of permeability, which may be easy to use but provide parameters that are not really repeatable and not linkable to basic magnitude. Such methods generally refer to Darcy's law [Bear, J., 1972], though in some cases the basic hypotheses are not met.

1.2 Permeability measurement of porous asphalt layer with water permeameters

The experiences documented in the area of hydraulic conductivity measurements in road surfaces which use water as reference fluid can be referred to two different typologies of instruments (permeameters), based on falling head devices and constant head devices.

The former typology of permeameters is mostly used for hot mix asphalt having limited permeability. The latter typology is mostly used for open-graded hot mix asphalt with 15 % void content.

Both typologies allow to calculate the permeability coefficient, in the former case on the basis of the time required for the filtration of a given water head, in the latter case on the basis of Darcy's law of fluid filtration through a porous field. This law is based on particular theoretical assumptions which are difficult to be met in field tests.

Darcy assumed that the flow occurs through a homogenous saturated material, the fluid is incompressible, and the flow is laminar, one-dimensional and under steady state conditions.

Frequently used in Italy because provided for in many tenders, is the water permeameter at 250 mm falling head test on an area of 154 cm^2, suited to quantifying the average *drainage capability* in dm^3/min, according to a specific procedure devised by the Società Autostrade [Capitolato Speciale d'Appalto Società Autostrade, 2004]. However, it is a conventional parameter that cannot be related to the permeability coefficient. A similar observation can be made about the Belgian Permeameter [Ministère des travaux publics, 1986]. These local procedures and equipements can be traced back to European Regulation [CEN EN 12697-40 (2005)].

There exist other systems [Cooley, A. 1999] which allow to determine permeability coefficient *k* in falling head conditions, but they apply to laboratory configurations and presuppone one-dimensional flow.

In these conditions the following relation applies:

$$k = \frac{a \cdot L}{A \cdot t} \cdot \ln\left(\frac{h_1}{h_2}\right) \qquad (1)$$

where:

k	=	coefficient of permeability	(cm/s)
a	=	area of stand pipe	(cm^2)
L	=	width of sample	(cm)
A	=	cross area of permeameter	(cm^2)
t	=	time over which head is allowed to fall	(s)
h_1	=	water head at start of test	(cm)
h_2	=	water head at end of test	(cm)

Recent experiments conducted by the authors [Giuliani, F. et al., 2006] have highlighted some theoretical problems typical of water permeability measurements on porous asphalt pavement in reaching the exact quantification of the permeability coefficient. In particular the assessment of the *anisotropic condition* of the drainage layer and the *saturated conditions* of such layer have appeared to be essential.

One-dimensional water permeability tests on specimens cored from slabs of porous asphalt concrete compacted in the laboratory along the compaction direction (orthogonal to the slab) and along the horizontal flow direction (coplanar to the slab), have allowed to determine the horizontal (kx) and vertical (kz) permeability coefficient (Figure 1).

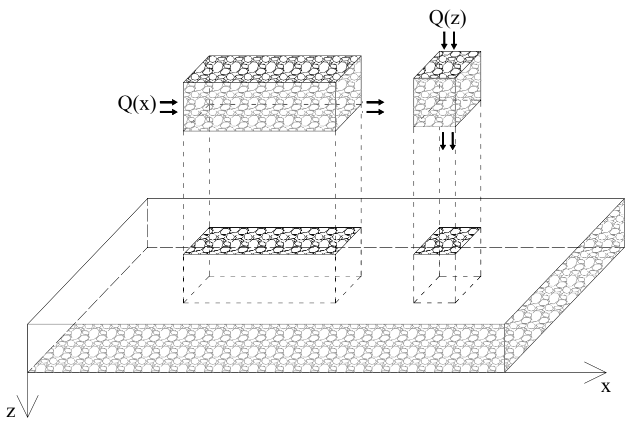

Figure 1 - One-directional filtration tests on porous asphalt concrete slabs

The tests were carried out in saturated conditions and in a configuration coherent with the hypotheses of Darcy's filtration law, and have highlighted significant anisotropy of porous asphalt slabs. A bidimensional study of flow through porous materials is therefore necessary.

In particular, in different compacting and grading distribution conditions, the permeability coefficient value defined in the horizontal surface (kx) was almost double the value calculated along the vertical direction (kz).

In order to correctly determine the permeability of porous asphalt layers it is of fundamental importance to verify the saturation conditions of the porous material, or, in a measurement carried out with water, it is essential that the flow starts in a material containing no air. In this case too, by means of a specific experimental apparatus, the constant head permeability tests, repeated on samples with different heights and through permeameters having different dimensions, have shown complete expulsion from the area within the porous asphalt mix after approx 30 min of continuous water flow [Giuliani, F. et al., 2006].

Therefore, the solution suggested with the measurement system using the Belgian permeameter and the one of the Società Autostrade, for the preliminary soaking of the drainage surface before the test, appears to be inefficient.

1.3 Permeability measurement of drainage surface by means of air permeameters

The use of fluids different from water [Cabrera, J.G. et al., 1988] can significantly reduce the duration of the temporary transitional periods that are necessary to reach the saturation condition indispensable for measuring permeability with a good degree of repeatability. By considering air as the fluid used to analyze the filtration process, it is possible to overcome the problem of coexistence of two different phases within the voids of porous layers.

The first permeameters to use air as measurement fluid for asphalt concrete permeability date back to the Eighties. Experiments conducted at that time led to the issue of the ASTM rule D 3637 – 84 (1991), which provides for two different test procedures: laboratory test and field test. The complicated set of tests and equipment necessary for the test prevented the diffusion of the method and its valid theoretical assumptions.

This complicated measurement equipment can be simplified by using innovative instruments suitable to check flow and pressure in the filtration process both easily and precisely.

In the following sections we will report on the calculation of air permeability according to Darcy's law of one-directional filtration of fluids through a porous material. ASTM defines *permeability* K according to the following equation:

$$K = \frac{Q \, \mu \, L}{A \cdot \Delta p \cdot \Delta t} \qquad (2)$$

Where:

K	=	permeability	(cm^2)
Q	=	volume of air forced through the sample and corrected to 1 atm of pressure	(cm^3)
L	=	thickness of sample	(cm)
A	=	area of sample	(cm^2)
Δp	=	pressure in the cell as measured with the manometer	(Pa)
μ	=	viscosity of air	(Pa·s)
Δt	=	time required for water level to drop from one mark on the sight tube to another	(s)

Tests on the road or on porous asphalt slabs assume a three-dimensional flow. The symmetry of the set can allow to study the filtration process in a bidimensional space. Therefore equation (2) can be used by means of a suitable numerical modeling.

2. AIR PERMEABILITY TEST BY MEANS OF A PROPER APPARATUS

A permeability test was set under strict laboratory conditions. The test was carried out by means of an air permeameter, working on portions of porous road pavements having significant size (0.25 m^2). The slabs of porous asphalt concrete were manufactured employing the asphalt mixture taken from the finishing machine on the Italian site on the A15 highway, compacted by using a heavy roller compactor.

The asphalt concrete, containing SBS hard modified bitumen in percentage of 4.15, showed a 17 % void content at the end of compaction.

The slabs manufactured were 4 cm and 6 cm thick. The prismatic samples realized were set on a stiff base that constituted an impermeable separator able to reproduce the configuration characteristic of a porous pavement in the field.

The tests were carried out using a permeameter formed by a vertical plexiglas cylinder stiffly joined to a horizontal base. The base was made of a plastic slab with a washer and had a weight as lock on it (Figure 2).

The test equipment simulated the conditions present on road pavement, where a three-dimensional flow takes place, characterized by radial symmetry as to the barycentric vertical axis of the permeameter. Once the device was placed on the surface to be investigated, the test was carried out. The test consisted in the introduction of an air flow from the top of the cylinder and then the reading of the value of the pressure generated above the sample at the permeameter base. The reading was done by means of four radial plugs, connected to a pressure transducer. The air was introduced into the permeameter by means of a flexible pipe joined to a valve for the regulation of the flow. The valve was electrically operated and fed by compressed air.

Data were acquired once a brief transitional periods was over, which lasted approx 2 minutes. During this time the flow stabilized and the portion of material which the flow went through could be considered saturated.

During this interval the system was calibrated, with the verification of the pressure in air inlet valves.

The air flow delivered was constantly controlled electronically by means of a jet valve connected to a control unit for data acquisition. All the measurement phases were regulated and monitored through a personal computer.

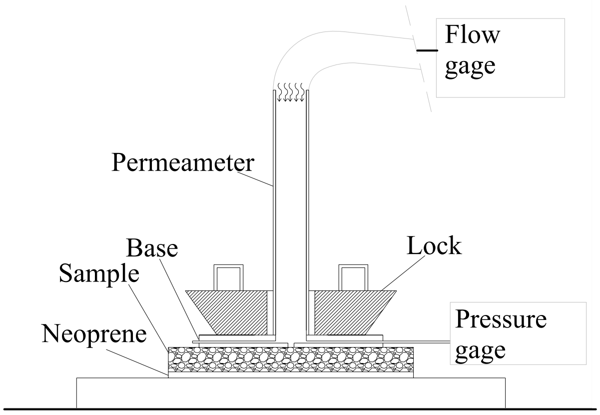

Figure 2 - Setting procedure with air permeameter

2.1 Choice of permeameter geometry

The experimental device employed was the outcome of a preliminary search for measurement repeatability, validating the choice of each component of the instrument used with the aim of obtaining the best arrangement between scientific value of the results and test procedure practicality. Of the different components of the device, the choice of the size of permeameter diameter, related to the size of the aggregates in asphalt concrete, was one of the most significant phases.

At the beginning the tests were carried out applying flow control, by manually operating the regulating jet valve placed before the inflow system.

Each permeability test was repeated on three different points of the slab surface, first using the permeameter with 24 mm diameter, then the size was changed to 32 mm and 48 mm. The aim was to find results that were not influenced by local conditions of the porous layer surface characterized by macro-roughness.

The graphs related to each permeameter were drawn on the basis of the measurements carried out, highlighting the trend of the pressure as a function of the flow present at the three test points (Figure 3).

Analyzing the pressure-flow curve, it can be observed that, for the same air discharge introduced, the pressure decreases with the increase in the permeameter diameter. This is due, for the same discharge, to the larger area of the pavement surface pertaining to the permeameter, i.e. the area of the section which the fluid can flow through.

The tests carried out through a smaller sized filtering surface highlighted very scattered curves; indeed, the greater the permeameter diameter compared to the maximum size of aggregates employed, the more the recorded data are representative of the mixture and not affected by local heterogeneity which may be present.

The curves obtained employing the 48 mm diameter permeameter yield a correct average of the permeability characteristics of the means studied and highlight the importance of the permeameter diameter used for the test.

Based on these results, the experimental procedure was finally carried out employing a 100 mm diameter permeameter.

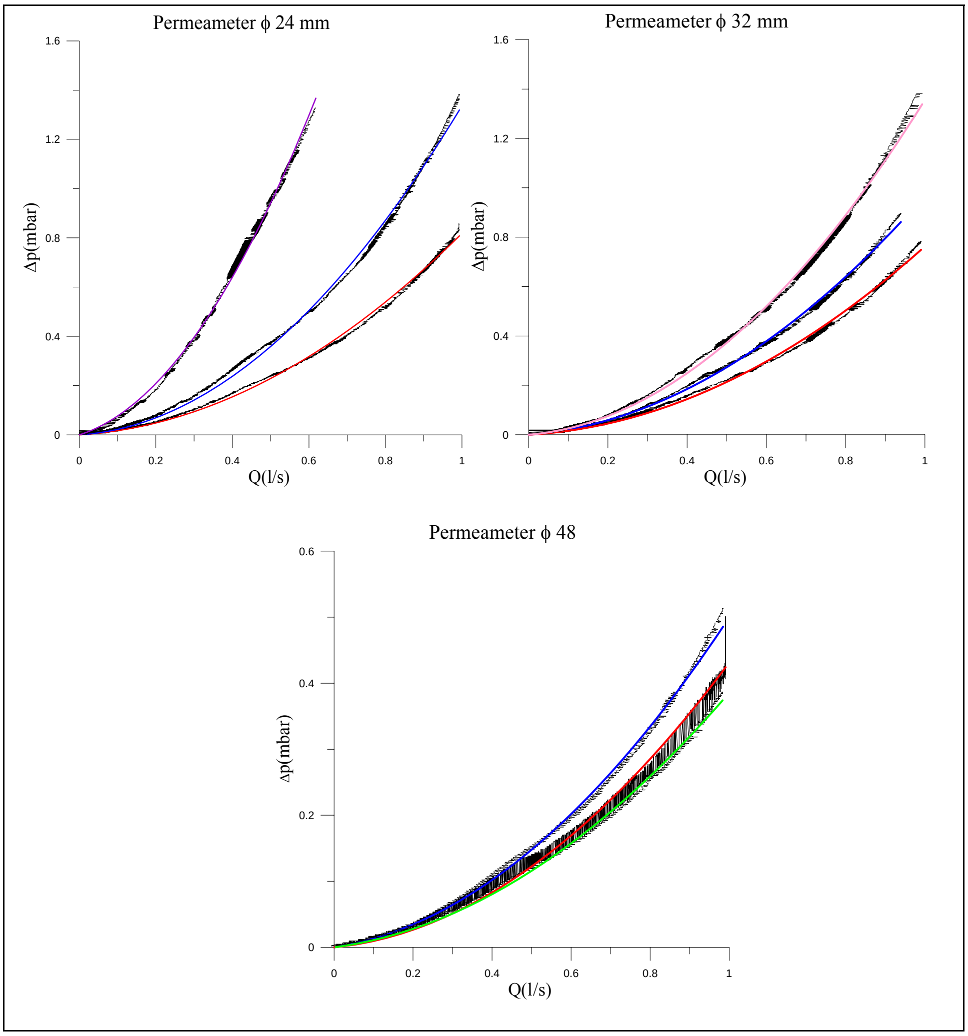

Figure 3 - Air permeability tests with different permeameter diameters

In order to verify the system's repeatability, nine tests were carried out on slabs 41mm and 63 mm thick. Each time the permeameter was placed on different points of the porous surface (Figure 4).

As can be seen by comparing the last graphs, the experimental curves obtained using the 48 mm diameter permeameter show lower variability in the results, due to the significant reduction in head loss.

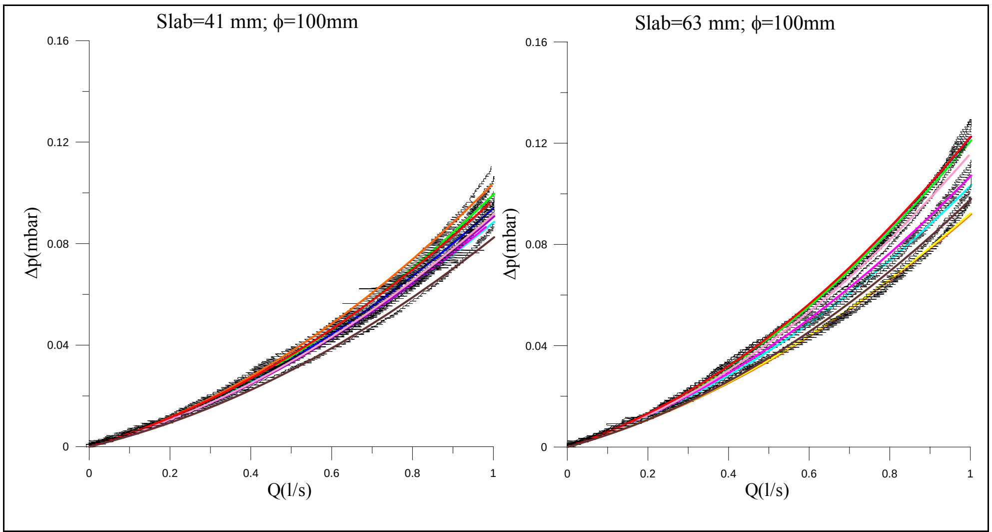

Figure 4 - Air permeability tests using 100 mm diameter permeameter

The experimental curves show good fulfillment of Darcy's Law hypotheses, indeed the trend of the Discharge-Pressure curves allows to identify a linear relationship between discharge and pressure up to discharge values of approx 0.17 l/s. Beyond this value the trend bilinear is expressed by the generic equation:

$$P = aQ^2 + bQ \qquad (3)$$

Once the test conditions were known, the conditions of laminar flow could be verified for discharge values lower than 0.17 l/s, calculating Reynolds's Number of air:

$$Re_{air} = \frac{V_{air} \cdot d}{\nu_{air}} \qquad (4)$$

where:

V_{air} is the air speed, d is the diameter through which the flow takes place and ν_{air} is the Kinematic viscosity of air ($10^{-5}\ \frac{m^2}{s}$).

Remembering that:

$$V_{air} = \frac{Q_{air}}{A} \qquad (5)$$

where:

Q_{air} is the maximum inlet air discharge (0.17 $\cdot 10^{-3}$ $m^3 s^{-1}$) and A is the area of permeameter section ($7.85 \cdot 10^{-3}$ m^2), the final value is $\mathrm{Re}_{air} = 22$. For such value of Reynolds's Number the flow can be considered laminar [Bear, J. (1972)].

The laboratory experimental analysis, aimed at the calibration of the test methodology and the acquisition of experimental data, is followed by a second phase in which the data obtained are processed by means of an analysis based on a finite element model for the reconstruction of the flow model that is able to overcome the limit of a one-dimensional calculation approach.

3. CALCULATION OF AIR PERMEABILITY COEFFICIENT BY MEANS OF FEM ANALYSIS

The test set requires a three-dimensional flow within the surface drainage layer of asphalt pavement.

The radial symmetry of the test set up allows to study the problem in two dimensions only, schematizing the porous medium to small portions by a mesh of finite, triangular elements whose vertices are at a distance of $2 \div 2.5$ mm (Figure 5).

The permeability coefficient of the porous asphalt mix is calculated by solving the physical problem by means of a finite element method with the program SEEP 2D, which is valid in the hypothesis of laminar flow.

The boundary conditions were subsequently fixed: free flow along the surface of the outside border at the base of the permeameter and a known value of pressure within the filtration area. Once the entering air discharge and the relative pressure value are fixed, both during the experimental stage, and the isotropy of the material is assumed, through a back-calculation process it was possible to determine the permeability coefficient of the porous medium.

Below are the k-Q curves obtained by representing the results of the modeling related to the experimental tests that were accomplished with permeameter Φ 100 mm on porous slabs of different thickness (Figure 6).

Analyzing the curves it can be observed that the slabs having 40 mm thickness show greater flow capability than the thicker sample (approx 60 mm), consistently with the physical phenomenon.

Both types of slabs, for discharge approx 0.17 l/min, show constant values of air permeability and these values are similar among themselves, thus confirming the hypothesis of laminar flow and the validity of Darcy's law.

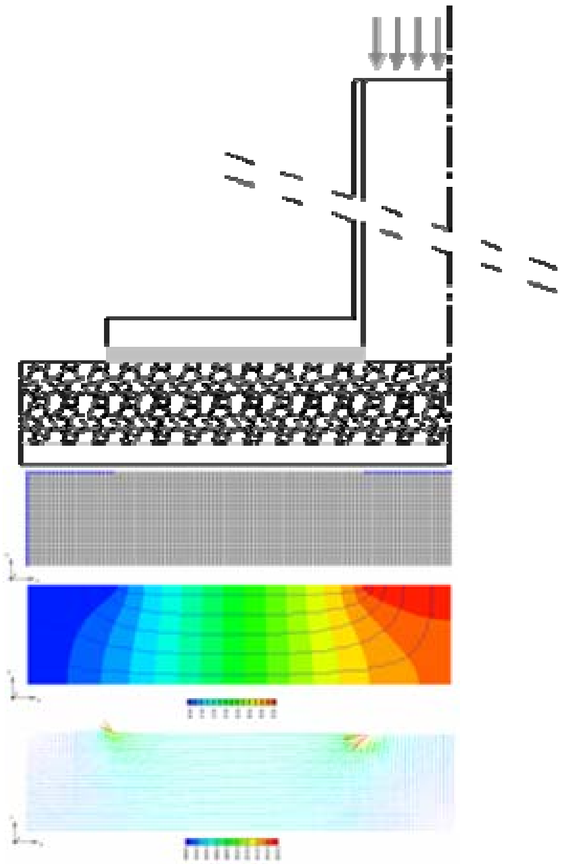

Figure 5 - 2D Modeling of air permeability test

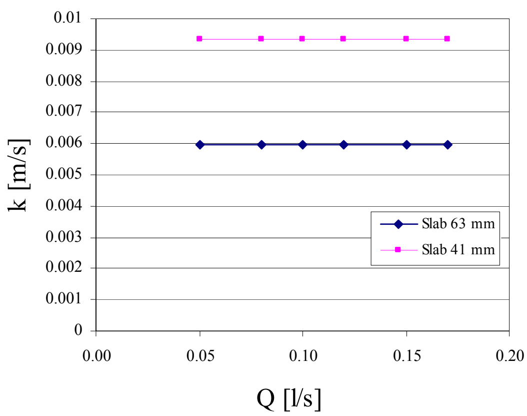

Figure 6 - Air Permeability k versus discharge for slabs of porous concrete having 41 mm and 63 mm thickness

3.1 Conversion of permeability values.

Having calculated the coefficient of air permeability Ki_{air} it was possible to express the relationship between this coefficient and the coefficient of water permeability K_{water} for the same porous medium in the same boundary conditions:

$$\frac{K_{air}}{K_{water}} = \frac{\gamma_{air} \cdot d^2}{\mu_{air}} \cdot \frac{\mu_{water}}{\gamma_{water} \cdot d^2} = \frac{\nu_{water}}{\nu_{air}} = \frac{10^{-6}}{10^{-5}} = 10^{-1} \qquad (6)$$

leading to:

$$K_{water} = 10 \cdot K_{air} \qquad (7)$$

4. CONCLUSIONS

The employment of air as fluid to be used in the study of the permeability of porous media, and in particular of porous asphalt mixtures, is undoubtedly a good choice, which by itself allows to overcome many practical and theoretical problems linked to the use of water.

The adoption of air systems limits the problems connected to the coexistence of phases in porous surfaces, and allows to quickly reach the saturation conditions of the porous means required by Darcy's hypotheses.

The use of air for *in situ* permeability measurements allows to remove the difficulties met in field due to the water supply on the road, and consequently adopt theoretical schemes for the filtration in constant head conditions.

The air permeability test devised in this research did not appear to be independent of the permeameter diameter. The same thing can not be affirmed about the effect of thickness of the layers on the value of permeability. Indeed it is necessary to increase the study on a larger numbers of specimens with different thickness and to increase more the precision of measurement.

Darcy's Law, often applied without the necessary attention in road applications, is significant only when the entire fundamental hypotheses are verified or correctly approximated.

The results obtained from the experimental investigation and the subsequent numerical modeling allow to draw the following conclusions:

- The permeameter section must guarantee the supply *in situ* of a fixed discharge and, at the same time, must not trigger undesirable size effects. Such effects are less relevant when the ratio between the permeameter diameter and the sample size increases, in both the size of plane and thickness. The suggested size of 100 mm for the permeameter diameter (more than five times the maximum nominal size of the stone aggregate in the mixture) has proved to be the best in describing the filtration process.

- For the original and rigorous fitting studied and for discharge values lower than 0.17 l/s, Darcy's Law hypotheses may be considered effective. This allows to determine the permeability coefficient of the slabs of porous asphalt mixture studied.
- The steady state flow established and the linearity of the relationship between pressure and air flow discharge of laminar type, allow to convert, when necessary, the value of coefficient of air permeability into the coefficient of water permeability.

REFERENCES

BEAR, J. (1972) – "Dynamics of fluids in porous media", Inc. New York, Dover Publications, USA.

CABRERA, J. G., LYNSDALE, C. J. (1988) – "A new gas permeameter for measuring the permeability of mortar and concrete", Magazine of concrete research. Vol. 40 N. 144.

Capitolato Speciale d'Appalto Società Autostrade, (2004).

COOLEY, A. (1999) – "Permeability of superpave mixtures: evaluation of field permeameters" – *National Center for Asphalt Technology,* Report No. 99-1, Auburn University, Alabama, USA.

CEN EN 12697-40 (2005) – "Bituminous mixtures – Test methods for hot mix asphalt" – Part 40 : In situ drainability, Brussels, Belgique.

CEN EN 13108-7 (2003) – "Bituminous mixtures – Materials specifications" - Draft Porous Asphalt, Brussels, Belgique.

GIULIANI, F., COSTA, A. (2006) – "Experimental evaluation of permeability of porous asphalt pavement in constant head condition" – Department of Civil Engineering, University of Parma, Italy

KANITPONG, K., BENSON, C., BAHIA, H. (2001) – "Hydraulic conductivity (permeability) of laboratory compacted asphalt mixtures" – *Transportation Research Board 80th Annual Meeting* Paper No. 01-2997, Washington, USA.

MALLICK, R., COOLEY, A., TETO, M., BRADBURY, R., PEABODY D. (2001) – "An evaluation of factors affecting permeability of superpave designed pavements" – *Transportation Research Board 80th Annual Meeting* Paper No. 01-2763, Washington, USA.

Ministère des Travaux Publics (1986) – "Enrobés drainants" – *Administration des Routes* Circulaire n° A-169-86/04000, Bruxelles, Belgique.

NCHRP (2004) – "Characteristics for use with performance related specifications for hot mix asphalt" – *National Cooperative Highway Research Program,* Research Result Digest 291, USA.