pressure (Pa); t = testing time; time for water to pass from start level to final level (s); k = concrete air permeability coefficient (m^2). Parameters employed in Thenoz methodology (Equation 1) are based in Darcy's law, a generalization of Poiseuille's law [13].

This equation contains some modifications because the fluid used is air. Darcy's law is integrated with correct air flow properties in porous media. These modifications also include variations in the air flow proportioned by slip effect and pressure gradients in inlet and outlet specimens during the tests [10].

EXPERIMENTAL PROCEDURES

Properties of the materials used in this study are shown in Table 1 and concrete properties in Table 2. Cement used was a blastfurnace slag portland cement, named CPIII 40, according to Brazilian Standards.

Concrete specimens were cast in cylindrical molds (100 mm diameter and 200 mm height) and remained in laboratory conditions (temperature of 23 ºC and 60% relative humidity) until the age of the tests. These specimens were cut and a slice of 100 mm diameter and 50 mm height, and the slices were used for air permeability test (Fig. 2). Air permeability and total porosity tests were carried out in concrete at the age of 28 days.

At the age of the test specimens were oven dried for 24 hours at 80º C, their lateral surfaces were sealed in order to guarantee that water was not present in concrete pores. Air flow at concrete specimens was only uniaxial and perpendicular to cross sectional area of the sample. Relations of the $\ln h_0/h_1=1$ in Equation 2 were employed in order to have a laminar flow [14].

Then, air permeability coefficients were obtained in accordance with Thenoz methodology and calculated in accordance with Equation 2.

Analysis of the Thenoz methodology was made in concrete specimens at four pressure gradients employed 7056 Pa, 6860 Pa, 6579 Pa, and 6272 Pa.

Air permeability was also calculated in a high strength concrete with another pressure gradient of 2492 Pa in order to show Thenoz methodology results.

RESULTS AND DISCUSSION

Parameters that demonstrate Mach and Reynolds number (Equations 3 and Equation 4, respectively) depend on velocity of the flow at porous media. Thus, fluid velocities of the flow were measured in accordance with Equation 3.

$$V = -\frac{k}{\mu}\frac{\Delta P}{L} \qquad \text{Eq. 3}$$

Flow velocity in concrete pores was measured with Equation 4, where flow velocity was divided by specimen porosity [15]. So, this represents air flow velocity inside the porous media.

$$V_{m_p} = \frac{V}{\varepsilon} \qquad \text{Eq. 4}$$

where: V_{m_p} = velocity average in the porous (m/s); S = cross-sectional area of specimen; and ε = porous media porosity

Air permeability coefficients (k), outflow average (Q_m) and velocity average in the pores (V) are shown in Table 3. Air permeability results show that they are modified when pressure gradients are applied for air permeability measurements.

Results obtained of the concrete air permeability (Fig. 3) show that it can change when different pressure gradients are applied. Concrete air permeability increases where the pressure gradient also increases.

Results show large values of air permeability. This indicates that the concrete employed in the tests had great porosity and capilarity and cannot be exposed to strong aggressive environment [16]. On the other side, high strength concrete shows better air permeability results (Fig. 8).

Flow velocity results also show that pressure gradients can change flow velocity (Fig. 4). It shows that their values increase with increase of pressure gradient. With this result, there is an increase in air velocity in the concrete pores. Increase in air velocity had similar growth as air permeability values. This behavior can be explained because flow velocity was obtained in accordance with air permeability constants, following Equation 3 [9].

Darcy's law

Flow mechanisms were analyzed plotting the pressure gradient applied *versus* the outflow average. Data are in accordance with Darcy's law if the plotted graphic is a straight-line and this line is passing through the origin [10].

As can be see in Fig. 5, pressure gradients employed in the tests *versus* outflow average show good results and the straight-line does pass close to the origin. This result demonstrates the validity of Darcy' s law in Thenoz methodology. However, such a method has to be very carefully validated before being used as a routine procedure. The validation process must include comparisons between the values obtained from a large number of concrete mixtures covering a wide range of mixture compositions.

Results of samples tested and tests carried out to validate Darcy's law in Thenoz methodology reported that this method had a good correspondence for concrete air permeability analyses proposed by Dullien [10] and parameters employed in Thenoz methodology were also valid, corresponding to the same flow mechanisms phenomena.

Mach number

Mach number is used for measuring air compressibility and air specific gravity variations in porous media during flow [17]. When Mach number (Equation 5) is less than 0.3, air compressibility during the flow might be ignored; when Mach number is greater than 0.3, flow must be considerate as compressible [11].

$$M = \frac{V_{f\,m}}{c} \quad \text{Eq. 5}$$

where: M is Mach number; V_{f_m} is flow velocity (m/s); and c is sound velocity at the air = 300 (m/s).

Results show (Fig. 6) that Mach number was lower than 0.3 and air compressibility during flow might be ignored [11].

Influence in Mach number also might be observed where pressure gradient is applied. High flow velocities can change fluid compressibility and modify air permeability results and Thenoz methodology cannot be applied.

High strength concrete results (Table 4) also show that the air compressibility effect in Thenoz methodology can be ignored, and their results were lower than other specimens tested (Fig. 9). All results shown that Mach number is lower than 0,3 and the air compressibility during the test can be ignored.

Reynolds number

Reynolds number (Re) (Equation 6) is indicative of the flow type (laminar, transient or turbulence flow). Reynolds number analysis in porous media is important because when Darcy's law is employed in mathematics equation, it is valid only when the flow is laminar. When flow not is laminar, Darcy's law can generate false measurements of porous media permeability.

Several works that evaluated flows in porous media have shown that turbulence may start with Reynolds number close of unity. However, deflections in Darcy's law begin to appear for Reynolds greater that 600 [18].

$$R = \frac{V_{f_m} d\rho}{\mu} \quad \text{Eq. 6}$$

where: R is Reynolds number; V_f is outflow velocity; d is hydraulic diameter (m); ρ is fluid specific gravity (kg/m^3); and μ is fluid viscosity at the test temperature (Pa.s).

In this work, the results show, as can seen in Fig 7, that the Reynolds numbers obtained in the tests were lower than 600. High strength concrete results show values closer to unity and, in a general way, the flow can be considerate as laminar [10].

Specimens with great porosity might have great flow velocity and great Reynolds number. In this case, the flow in specimens can be accepted as laminar, but a large number of samples must be tested because this value may invalidate Darcy's law.

Results obtained from this experimental work show that specimens of both low and high strength concrete with high and low porosity have flows that are laminar. However, high strength concrete results show better results and flow can be considerate as purely laminar (Fig. 10) [16, 17, 19].

CONCLUSIONS

In this work tests were carried out to observe Thenoz methodology to analyze concrete air permeability. In order to do so, several parameters were chosen to calculate and validate this methodology as Darcy's law, flow velocity, Mach and Reynolds number. This methodology was applied in two kinds of concrete: a low strength concrete and a high strength concrete.

Different pressure gradients were employed and showed that air permeability and flow velocity could change when different pressures were applied. Both air permeability and flow velocity increase where the pressure gradient is also increased.

Plotting results of outflow *versus* pressure gradient show that Thenoz methodology and parameters employed can be used for measuring concrete air permeability and that Thenoz methodology is in accordance with Darcy's law.

Mach number results show that air compressibility can be ignored during concrete tests air permeability tests in accordance with the methodology proposed by Thenoz.

Reynolds number results show lower values for high strength concrete and, in this, specimens flow mechanisms can be considerate as purely laminar.

For samples tested in this work, with both porosity and air permeability coefficients, Thenoz methodology and parameters employed show their validity. However, such a method has to be very carefully validated before being used as a routine procedure. The validation process must include comparisons between the values obtained from a large number of concrete mixtures covering a wide range of mixture compositions.

ACKNOWLEDGEMENTS

Acknowledgement is given to the National Council of Development Scientific and Technological (CNPq – Brazil, Process 13850/2006-4) and to the School of Civil Engineering, Architecture and Urban Design of the State University of Campinas, where tests took place.

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Table 1 – Material properties

Materials	Properties
Cement CP III – 40	Fineness (*% retained Sieve # 200*)..........95,8 Blaine (cm^2/g)..........682,63 Specific Gravity (g/cm^3)..........2,99 Initial Setting Time (*h:min*)..........2:57 Final Setting Time (*h:min*)..........4:37 Normal Consistency (*w/c*)..........0,31
Fine Aggregate	Fineness Modulus..........2,53 Maximum Size (*mm*)..........2,40 Specific Gravity (g/cm^3)..........2,60 Bulk weight (g/cm^3)..........1,43
Coarse Aggregate	Fineness Modulus..........3,38 Maximum Size(*mm*)..........19,0 Specific Gravity (g/cm^3)..........2,99 Bulk weight (g/cm^3)..........1,52

Table 2 – Concrete properties

Concrete	Low strength	High strength
Mix Proportions (in mass) (cement: fine aggregate: coarse aggregate)	1:3:5	1:2:3
Water/cement (in mass)	0.42	0.42
Water reducing admixture (kg/m^3)	3.0	1.7
Cement content (Kg/m^3)	266	396
Compressive Strength (*MPa*)	13.0	65
Total Porosity (*%*)	6.2	1,5

Table 3 – Permeability, outflow and flow velocity

Pressure Gradient (*Pa*)	Average permeability *k* ($m^2 \times 10^{-13}$)	Q_m (m^3/s)	V ($m/s \times 10^{-2}$)
7056	7,39	3,40	2,70
6860	8,52	5,56	4,38
6579	9,25	4,20	3,34
6272	9,70	3,50	2,79

Table 4 – Permeability, outflow and flow velocity, Mach number and Reynolds number for high strength concrete

Pressure Gradient (Pa)	Permeability ($m^2 \times 10^{-15}$)	Outflow ($m^3/s \times 10^{-3}$)	V ($m/s \times 10^{-4}$)	Mach Number ($\times 10^{-6}$)	Reynolds Number
2492	6,87	1,97	3,05	1,02	1,01
2492	7,42	2,15	3,30	1,10	1,09
2492	7,38	2,13	3,28	1,09	1,09

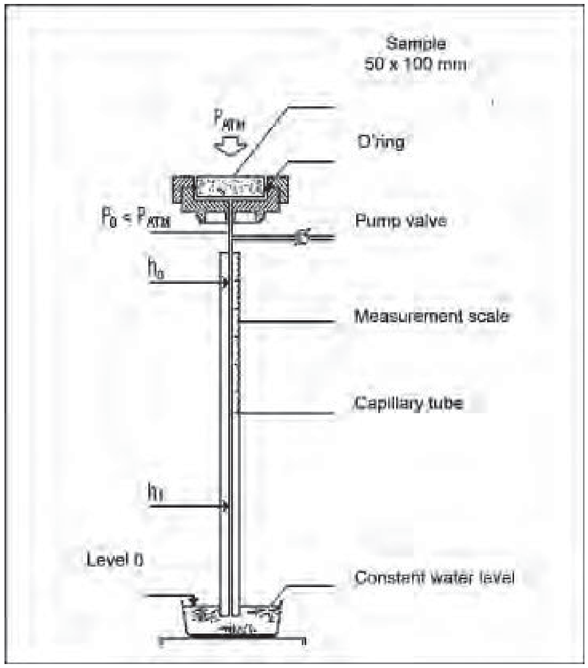

Fig. 1 – Permeameter used in Thenoz methodology (PERRATON 1989).

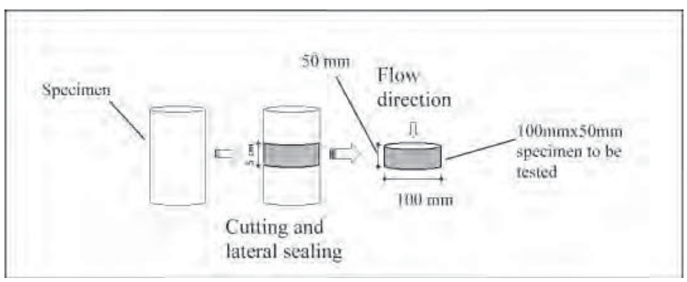

Fig. 2 – Specimen preparation for permeability test.

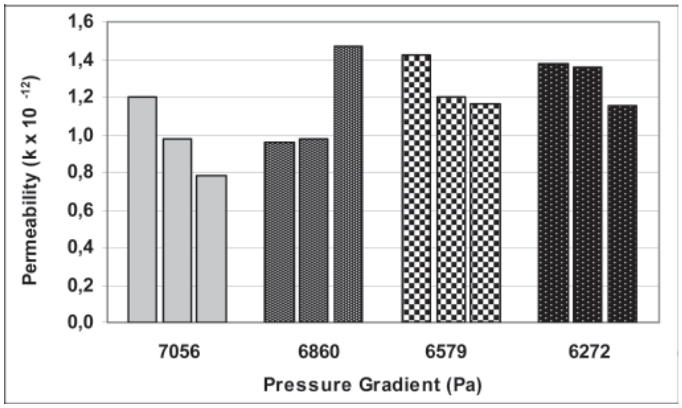

Fig. 3 – Air permeability results.

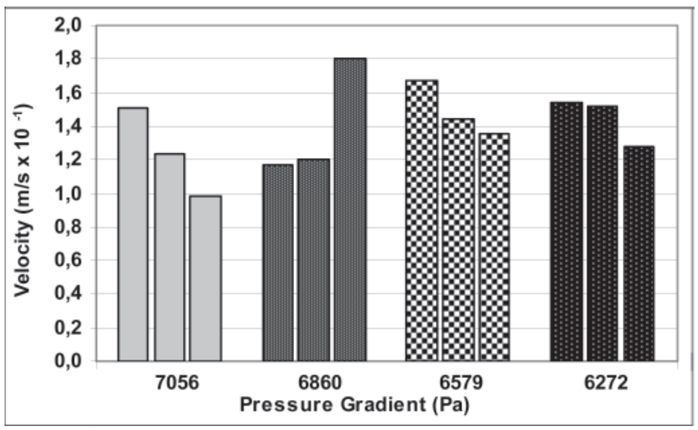

Fig. 4 – Flow velocity results.

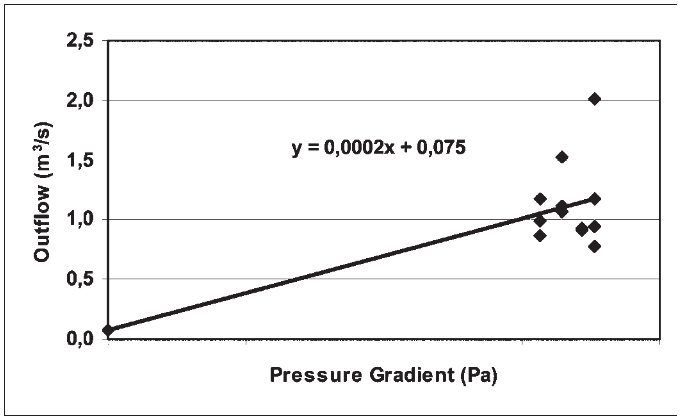

Fig. 5 – Darcy's law analysis in concrete results.

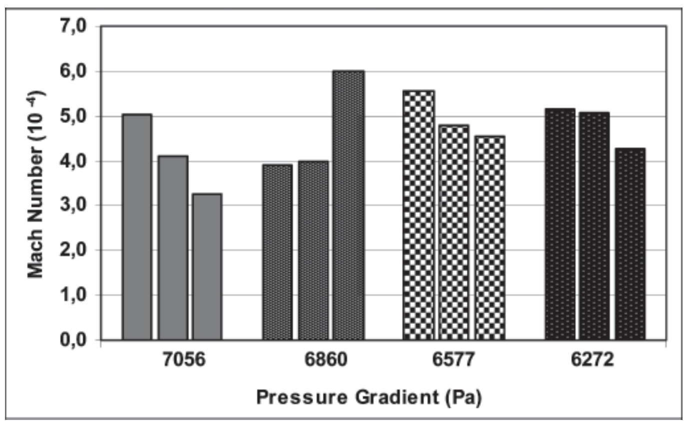

Fig. 6 – Mach number results.