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# One century of theoretical and applied mechanics of concrete and stone materials permeability. What have we learned?

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**Abstract.** Periodic and non-routine inspections on buildings, infrastructures, and sites of historical or architectural interest frequently involve a necessary deepening of the knowledge of natural or artificial stone materials of the built heritage. Insight into stone materials is of particular relevance when the problem is approached of fine-tuning best practices for assessment and maintenance within Life Cycle Assessment methodologies, in the light of an increased awareness that social, infrastructural and environmental issues and policies cannot be faced by single compartments but need comprehensive evaluation. Permeability has been early recognized as a basic property for the assessment of durability of concrete and stone materials. This contribution reports and discusses selected conclusions of studies which have scrutinized a large body of theoretical and technical scientific literature on permeability testing of concrete, as well as of regulatory literature, keeping a historical perspective and a focus in pinpointing fundamental open research issues of both theoretical and applied relevance in the mechanics of permeation of fluids through porous media. The fundamental experimental studies conducted in the first decades of last century are also the starting point for an assessment of the continuum mechanics and thermodynamics equations describing the flow of compressible fluids in porous media and for a critical review of the approach of current European standards to the determination of concrete watertightness.

## Introduction

The first published documents reporting of studies on concrete permeability can be traced back to the first quarter of the last century and were mainly devoted to verifying the applicability of Darcy's law to water permeability for this porous construction material which was new, or considered new, at the time. The work by Withey and Wiepking [1] together with other remarkable experimental studies developed in the U.S.A., among others by McMillan and Lyse [2], Ruettgers et al., [3, 4], and Vidal and Samson [5], were all devoted to find a suitable test setup and methodology to correctly evaluate the intrinsic permeability and the material and testing parameters influencing experimental results. The porous nature of concrete was well understood, and its watertightness was considered essential for the efficiency of strategic constructions like dams and bridges. In the same years, in Europe, experimental works developed in the U.K. by Glanville [6] and Madgwick [7] and in France by Mary [8] were carried out on the subject of concrete and stone permeability. Although the testing apparatuses and the tested stone and concrete materials were different, all these research efforts were focused on the identification of regularly observable phenomena and material properties. The only common features shared by the different experimental procedures were the creation of a uniaxial steady-state flow through a porous medium specimen acting like a filter under open-flow conditions and having, in general, a tile-like shape with thickness generally lower than 5 cm. These common features had, among others, the objective of maximizing the fluid flow in order to facilitate measurement by conveniently reducing error factors, like the formation of air pockets, as well as testing duration.

A comprehensive treatise on the flow of homogeneous fluids through porous media, with a focus on large-scale geological problems also of multiaxial nature, was published by Muskat [9] while studies focused on the correlation of permeability to microstructural parameters of the stone filter were successfully developed by Kozeny [10] and Carman [11]. It is worth remarking that all these studies gave for granted that the experimental determination of permeability is to be obtained by set-ups enforcing uniaxial steady-state open-flow conditions. Additional phenomena introducing deviations from the basic Darcy's formula, determined by the use of gases as permeating fluids, were later investigated by Klinkenberg [12]. Studies dedicated to Portland cement pastes were carried out by Powers et al. [13, 14]. Hallmark of the subsequent period from the fifties of the past century onwards, concerning permeability testing in concrete, was the evolution of tests in the wake of standardization processes controlling the transfer to a broader public of knowledge and procedures from scientific, industrial and engineering corps' research. For instance, one important regulative publication in this standardization process was the Initial Surface Absorption Testing methodology (ISAT) [15]. The main aspects to be underlined of this subsequent period are a partial renouncement to pressure-cells and set-ups granting strict conditions of uniaxial open flow (see, for instance, Levitt [16]), the renouncement to thorough oven drying of all specimens before test, the attempt to accommodate nondestructive on-site testing (Figg [17]), and a general push towards practices for concrete watertightness testing having a much more conventional character. It is necessary to wait the end of the '80s to find a study by Dhir et al. [18] performing a review of the ISAT and Figg's techniques and a partial reconnection with past methods based on the quantitative determination of intrinsic permeability by steady state uniaxial flow transmission. The results of the above-mentioned trend of pushing towards more conventional practices for concrete watertightness testing can be observed at present times examining the codes actually in force in the EU, almost all derived from EN 12390-8:2019 [19]. Most codes and combined provisions are based on just measuring the penetration, after splitting test, of the depth of water in an almost 10 cm deep concrete specimen, after a 72 hrs constant pressure.

A comprehensive critical review of one hundred years of permeability tests has been recently carried out by Monaco et al. [20] with the objective of assessing a near-zero-invasiveness practice which is therein proposed for the Life Cycle Assessment (LCA) of concrete structures and building manufacts by integrating actions of surveying, sampling, and watertightness testing of a concrete cover object of appraisal for possible replacement.

This contribution reports and discusses selected conclusions by Monaco et al. [20], keeping a focus in pinpointing fundamental open research issues of both theoretical and applied relevance in the mechanics of permeation of fluids through porous media with some critical considerations on current European standards for the determination of concrete watertightness. Given the importance of uniaxial flow, the document also reports in brief the main conclusions of an assessment of the continuum mechanics and thermodynamics equations describing uniaxial open-flow permeation of compressible fluids in a porous filter (Serpieri and Monaco [21]).

## Fundamental mechanical quantities and phenomena in stone permeability testing

As reviewed in Muskat's treatise [9], the permeation of an incompressible liquid through a cylindrical filter made of a macroscopically homogeneous porous medium saturated by a Newtonian fluid – under the usual hypotheses of stationary conditions, macroscopically uniform, uniaxial and nonturbulent flow – is well described by Darcy's linear relation, depending on the permeability $K_P$, a proportionality constant (in $[m/s]$) which is characteristic of the porous medium and which also depends on the fluid properties. For incompressible liquids, the pressure gradient and the velocity are uniform through the filter length and Darcy's relation can be conveniently expressed in the form containing the intrinsic permeability which has the dimension of square meters. As shown in the theoretical and experimental studies by Kozeny [10] and Carman [11], in complete saturation the intrinsic permeability is reasonably well predicted by a correlation with the specific surface area and the void volume fraction. It should be remarked that the valid predictive character of Carman's correlation has been successfully verified not only for granular beds of highly controlled geometry, investigated in the original works, but also subsequently for hardened concrete pastes by Powers and Brownyard [13]. These Authors have shown that, by assuming porosity to be equal to the nonevaporable water and by applying the method by Brunauer, Emett and Teller [22] to acquire measures of the specific surface of solid boundaries from the experimental determination of adsorption isotherm curves, a reasonable prediction is obtained of lowest intrinsic permeability values, in the range $[10^{-18}, 10^{-19}]\ \mathrm{m}^2$, inferable from experimental data on cement pastes reported by Ruettgers et al. [4] concerning the concretes employed in the construction of the Colorado Boulder 'Hoover' dam. Water-adsorption-related phenomena entailing deviations from the fundamental equation were studied by Carman [11] and Zunker [23], while the following compact expression of the deviation of intrinsic permeability for Portland cement pastes due to adsorbed water represents the results tabulated by Powers and Brownyard [13]:

$$K_{Pi} = 5.96 \cdot 10^{-22} \cdot \left(\frac{w/c - 0.15}{0.038} - k_1\right)^3 \cdot \frac{1}{w/c + 1/3.16}, \tag{1}$$

where $w/c$ is the water-cement ratio and $k_1$ is a parameter varying from 1 to approximately 4 tentatively accounting for the possible reduction of space available to transmission due to adsorbed water. A relation which predicts a deviation from Darcy's equation when the testing fluid is compressible, such as in air-permeability testing, and when conditions are isothermal was proposed by Muskat [9]:

$$\left(\bar{v}_{f1}\right)_{gas,Musk.} = \frac{dQ}{dt} \cdot \frac{1}{A} = \frac{K_{Pi}}{\mu L} \cdot \frac{(p_1^2 - p_2^2)}{2p_1}. \tag{2}$$

where $p_1$ and $p_2$ are the inlet and outlet velocity, respectively, $A$ is the cross-sectional area, $\mu$ the viscosity and $L$ the filter length. The close adherence of Eq. (2) to experimental data had been earlier verified by Madgwick [7] in studies on the permeability of several construction materials like building stones, bricks and plasters. It should be noticed, however, that while Madgwick derived (2) by never explicitly mentioning an isothermal hypothesis, Muskat [9] proceeded explicitly from such a hypothesis. A second deviation, observed only with gases, was shown by Klinkenberg [12] who theoretically derived and experimentally validated relations capable of accounting for a flow increment due to the so-called phenomenon of gas-slippage.

For water permeation, two further possible side-phenomena which, depending on the stone constitution and the test duration, may affect a regular steady permeation, and thus should be considered prior to an open-flow permeation test, are: 1) the decrease of permeability to water along test run time, termed by some authors "self-sealing", and 2) the opposite phenomenon of "self-unsealing" which is a gain of permeability during the test. The root causes for a same observed self-sealing or self-unsealing behavior can however be of very different mechanical or chemical nature. In concretes, the possible presence of unhydrated reactive cement fractions is a main common cause for self-sealing [2]. Hearn et al. [24] provided important insights on further factors, other than cement paste hydration, which might determine a permeability reduction, including: clogging, osmotic pressure, precipitation of soluble hydrates, chemical interaction between the water and the cement matrix, dissolution of air into permeating water, and incomplete saturation of the test specimen.

Self-unsealing can be originated by leaching of significant fractions of soluble components possibly present in the stone matrix and, although deserving the utmost attention for stone durability, appears instead to be a much less investigated phenomenon. El-Dieb and Hooton [25] recorded the variation of water-permeability as function of time in three concrete mixes. Their study exemplifies a typical graph of the recorded coefficient of permeability (in m/s) plotted versus the time at which permeability is measured, and shows that, during 80 hours testing, permeability undergoes an almost ten-fold increase probably ascribable to dissolution or transport of soluble components.

**A general model of uniaxial permeation of liquids and gases through stone materials**

A continuum mechanics theory of permeation of a fluid phase in a porous medium which is sufficiently general to address the case of a compressible fluid and which, proceeding from the consideration of a minimum possible number of kinematic descriptors, is also purely-mechanical, purely variational and purely macroscopic (in that it does not require a detailed knowledge or detailed assumptions on the small-scale features of the porous medium and of the solid-fluid interaction) has been derived by Serpieri and Travascio [26] on the basis of canonic variational arguments and of preceding studies by Serpieri and Rosati [27], Serpieri et al. [28]; and by Travascio et al. [29]. For compelling page limits, only the final set of equations governing the stationary thermomechanical variational statement of the uniaxial permeation of an ideal gas is synoptically reported below.

$$\hat{\rho}_f \bar{v}_f = \hat{\rho}_{f0} \bar{v}_{f0} \qquad \text{Complete space saturation + stationary Eulerian mass balance} \tag{3}$$

$$\hat{J}_f = \frac{\hat{\rho}_{f0}}{\hat{\rho}_f} \qquad \text{Lagrangian mass balance} \tag{4}$$

$$-p' - \frac{\mu}{K_{Pi}} \bar{v}_f = \hat{\rho}_f \bar{v}_f \bar{v}_f' \qquad \text{Linear momentum balance under stationary conditions} \tag{5}$$

$$\frac{\hat{\rho}_{f0}}{M} C_v T' \bar{v}_f = k_T T'' - p \hat{J}_f' \bar{v}_f \qquad \text{Energy balance under stationary conditions} \tag{6}$$

$$p = \frac{\hat{\rho}_{f0} R}{M} \frac{T}{\hat{J}_f} \qquad \text{Ideal gas law} \tag{7}$$

In the equations above, $\hat{\rho}_f$ is the true fluid density, $\bar{v}_f$ is the seepage velocity ($\hat{\rho}_{f0}$ and $\bar{v}_{f0}$ being reference values), $\hat{J}_f$ is the finite volumetric strain of the fluid, $M$ is the molar mass of the gas, $T$ the absolute temperature, $C_v$ is the constant-volume heat capacity of the fluid, $k_T$ its thermal conductivity, $R$ is the universal gas constant, and prime notation indicates space derivation as usual.

Serpieri and Monaco [21] have shown that the system above can be reduced to the following single differential equation in the only unknown $p$:

$$\frac{K_{Pi}}{\mu} \frac{1}{k_T} \frac{\hat{\rho}_{f0} R}{M} \left[ \frac{C_v}{R} (pp')' + pp'' \right] p' + (pp')'' = 0 \tag{8}$$

which, upon integration and approximation of negligible terms, provides a temperature-dependent solution encompassing deviations from the basic isothermal formula (2). Such solution can be employed to derive correlations applicable to the technical problem of air-permeability measurement in thin concrete filters which can be obtained from specimens carved out from an ordinary concrete cover.

**Discussion**

In the light of the studies herein summarized, research issues having both theoretical and applied relevance in the mechanics of stone permeability – in particular for concrete –, which are judged to be still-open or deserving further elucidation are:

- the definition of a general permeability measurement protocol capable of discerning the presence of a self-unsealing, self-sealing or stationary behavior in a given concrete specimen of tile-like form from recordings of permeability during a test of suitable duration;

- the determination of bounds to experimental and theoretical uncertainties associated with the possible occurrence of phenomena of self-unsealing and self-sealing;
- the definition of an experimental protocol, based on permeability variations, capable of discerning the possible presence of fractions of unhydrated cement and of swelling constituents in a given concrete mix.

A final comment is devoted to most recent and currently active standards, such as EN 12390-8, [19], which are based on a conventional measurement of penetration depth. The literature review has shown that intrinsic permeability by open-flow tests should be preferred, as a diagnostic parameter, to penetration depth since the former is less affected than the latter by hygrothermal and environmental factors.

The invasiveness of the size of the specimens, even 10 cm deep, prescribed by some recent standards is also pointed out in the light of the evidence that many testing protocols of the past have successfully employed much thinner specimens setting a path for the definition of less invasive standards.

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