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9 Gas permeability

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9.1 Measurement principle

The effective, or relative, gas permeability of a partially saturated porous media depends on the amount of available porosity for gas percolation, its connectivity, tortuosity and pore throat diameter. It is well known that gas permeability varies significantly with the distribution and the amount of moisture present in the porous network Abbas et al (1999), Dana & Skoczylas (2002). As illustrated in Figure 9.1, existing literature shows, Chen et al (2012) that in a first approach, for a given cementitious material, gas relative permeability can be seen as depending on the water concrete saturation only.

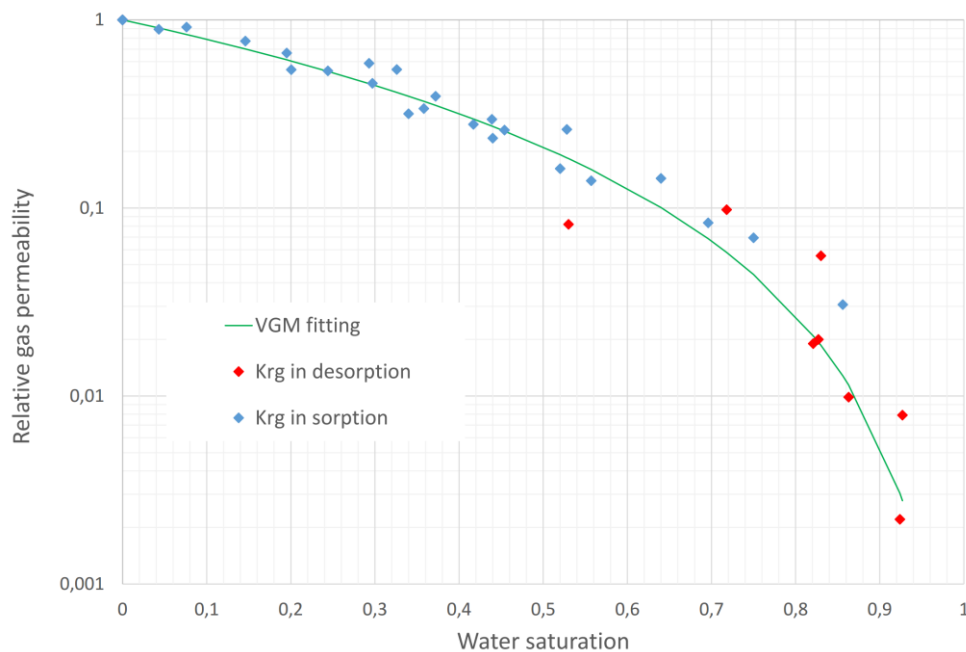


Fig. 9.1 Relative gas permeability K_{rg} vs. degree of water saturation S_w for CEM-V concrete: during desorption and sorption paths at, respectively, 120, 340, 490 days, Chen et al (2012).

Following these results it was thought that an efficient measurement method of in-situ concrete water content could be designed and based on gas permeability evaluation and variation. This method has been applied in a recent publication by Liu et al (2013) and is designated as “Pulse Test Protocol”. The moisture content measurement protocol lies in three steps:

- Defining the characteristic $K_{r,g}(S_w)$ -curve of the tested material,
- Measuring in situ effective gas permeability k_{eff} ,
- Deducing the moisture content of the material S_w .

9.2 Need for calibration

The characteristic $K_{r,g}(S_w)$ -curve of the tested material is an essential data. Those curves can either be obtained using predictive models (based on Mercury Intrusion Porosimetry for example) or through direct experimental characterization. Predictive models can be successfully employed to fit experimental points to obtain a complete $K_{r,g}(S_w)$ -curve useful for simulation purpose, but an experimental characterization campaign is strongly recommended to ensure acceptable moisture measurement accuracy.

9.3 Calibration techniques

To obtain the $K_{r,g}(S_w)$ -curve, routine laboratory gas permeability measurement have to be realized on samples with various homogenous moisture content. The range of studied moisture content can be adapted to the expected in situ range of moisture content. Various existing experimental apparatus can be used for this purpose, with various sample size, geometry and accuracy Martin (1986) Lydon (1993), Skoczylas & Henry (1995), AFREM (1996), RILEM (1999-b), Meziani & Skoczylas (1999), Loosveldt et al (2002), Lion et al (2004), Choinska et al (2007) and Gardner et al (2008). Kaczmarek (2008) and Kaczmarek (2010) have proposed schematic views of the most frequent experimental conditions, cf. figure 9.3.

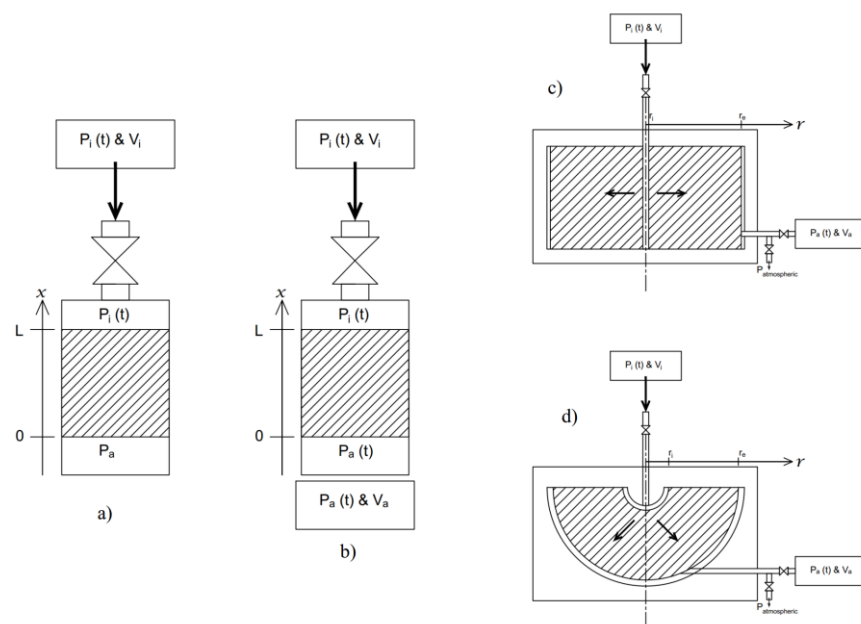


Fig. 9.3 Schematic configurations of single-reservoir (a) and double-reservoir (b) methods in for uniaxial flow, Kaczmarek (2008), and reservoir tests for cylindrical (c) and spherical (d) geometry of samples, Kaczmarek (2010)

9.4 Parameters measured

Once obtained the $K_{r,g}(S_w)$ -curve, a sole parameters has to be measured in order to obtain the moisture content: it is the effective gas permeability. The effective gas permeability is measured by applying one of the existing measurement techniques that can be found in literature. Among numerous available tests to assess the permeation

properties the concrete cover on site, we can cite, the “Vacuum Permeability Test” Claisse et al (2003), the Torrent permeability test, Torrent (1992) and Romer (2005), the “Autoclam Water and Air Permeability Test”, see figure 9.4.1), the “Figg Air Permeability Test”, the “Schönlin Air Permeability Test” or the “Surface Air Flow Test”, all reported by Henderson et al (2004).

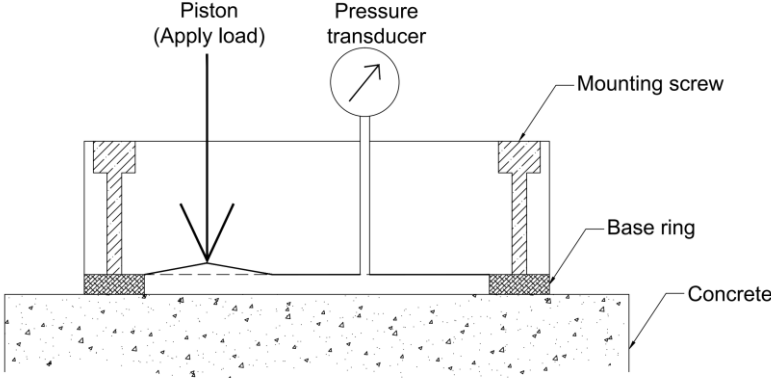


Fig. 9.4.1 Schematic of Autoclam test for air permeability, Henderson et al (2004).

More recently, a test has been developed to measure gas permeability in the core of concrete structures Liu et al (2013), see Figure 9.4.2.

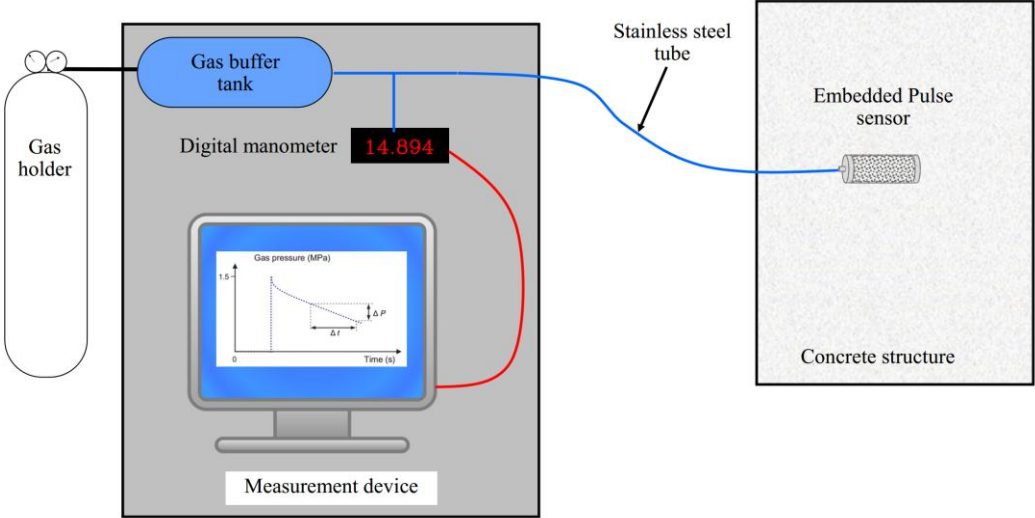


Fig. 9.4.2 Schematic view of the pulse measurement protocol, Liu et al (2013).

For a more detailed overview of existing tests see previous RILEM TC publications RILEM (1999a), Paulmann & Molin (1995) and RILEM (2007).

9.5 Measuring range

The measuring range mainly depends on the accuracy of the volumetric flow measurement accuracy. The effective gas permeability of concrete can vary from 10^{-16} m^2 (equivalent to 0.1 mD (D=Darcy)) for a dry low quality concrete to $10^{-19} - 10^{-20} \text{ m}^2$

(0.1 – 0.01 μD) for medium to high quality concrete with relatively high moisture content. In fact there is no lower limit for effective gas permeability as a fully water saturated concrete has a null gas permeability. In theory, with the appropriate measurement apparatus the whole moisture range can be measured. In practice, for classical structural concretes, when using available in situ gas permeability measurement apparatus, moisture contents ranging from 0 to 80-90 % can be measured.

9.6 Required time

The required time depend on the test duration necessary to obtain a sufficiently accurate evaluation of the gas flow rate. For high flow rate, a few minutes can be sufficient, while one hour or more can be necessary when testing low gas permeability materials, i.e. high quality concrete or with high moisture content.

9.7 Representative volume

The investigated volume depends on:

- the chosen gas permeability measurement apparatus,
- the duration of the test: the longer is the measurement the larger is the investigated volume,
- the effective gas permeability of the material: the more permeable is the material, the larger the investigated volume (for a given test duration).

The approximate size of the investigated volume can then range from a few cm^3 to several dm^3 .

9.8 Sources of errors

The main source of error is an inappropriate characteristic $K_{r,g}(S_w)$ -curve. This may be due to:

- the use of an unsuitable predictive models,
- an inaccurate gas permeability apparatus,
- a laboratory characterization performed on a material which is not representative of in situ material: unsuitable storing conditions, concrete sampled from a different batch, casting defects in the area where gas permeability is measured, etc.

For surface measurement using vacuum methods, high water saturation can lead to overestimation of the intrinsic permeability, Romer (2005).

Furthermore, the existence of gradients of relative humidity in the near surface concrete can lead to misleading results for surface measurement devices, Basheer & Nolan (2001). Methods have been investigated to deal with those gradients. Coupling together surface permeability measure with NDT-methods giving information on the existence and shape of relative humidity gradients, may significantly improve the quality of the measurement.

Micro-cracking can also lead to important differences between the $K_{r,g}(S_w)$ -curve of a sound laboratory sample and the one of the in-situ concrete. The influence of micro-cracking on the mass transport properties of concrete has been largely studied Abbas et al (1999), Burlion et al (2003), Jacobs (1998), Picandet et al (2001, 2009), Samaha & Hover (1992) and Wu et al (2015). A large increase of apparent gas permeability is then observed when micro-cracking occurs, and the $K_{r,g}(S_w)$ -curve obtained on sound concrete is no more valid. This micro-cracking may be caused by drying shrinkage, de Sa et al (2008), Burlion et al (2003), or mechanical loading, Picandet et al (2001). Furthermore, other studies have shown that the effect of cracks on gas permeability is not reversible even when a mechanical loading is applied in order to reduce cracks opening, Chen et al (2013), and Wang et al (2014).

Other sources of error strongly depend on the chosen in situ gas permeability apparatus and its flow rate measurement accuracy.

9.9 Commercial availability

In theory, once an appropriate characteristic $K_{r,g}(S_w)$ -curve of the material is available, any gas permeability device is suitable as long as its flow rate measurement range match with expected effective permeability.

In practice, the “Pulse Test” apparatus presented by Liu et al (2013), is the only gas permeability measurement device which has been used to determine the in situ moisture content of a concrete structure.