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A LABORATORY AND ON-SITE TEST METHOD FOR AIR PERMEABILITY OF CONCRETE

P. Paulini

Section of Material Technology, Faculty of Civil Engineering and Environmental Science, University Innsbruck, Austria

Abstract

The accuracy of permeability measurements in concrete depends crucially on a precise determination of the flow volume. By measuring the pressure drop in a vessel and calculating the air flow volume from these data the accuracy of test results is increased substantially. A pressure step technique is being used under steady state flow conditions and test data are analysed according to a new transport law. Two material parameters are used to describe the air flow in concrete. Based on laboratory permeability data the w/c ratio of the concrete mixture and the pore structure can be estimated fairly accurately.

On-site permeability tests are usually based on vacuum methods with non steady state flow conditions. The proposed Packer test uses a bore hole to fix a gasket with an injection packer on the member surface. Air pressures of up to 10 bars are applied under steady state conditions. The flow field is radially symmetrical over a wide range and a pressure gradient can be defined to analyse flow data. Practically all in-situ permeability tests are influenced by concrete humidity. Permeability data of on-site tests are scattered over a wider range compared to laboratory methods, but they are still a reliable indication of concrete quality.

1. INTRODUCTION

The damage of concrete usually proceeds from free exposed surfaces and is often caused by capillary transport processes in the pore system. Physical or chemical damage mechanisms can lead to substantial damage of concrete materials especially if they occur cyclically. Reactive gaseous or fluid media cause material deterioration or produce capillary pore pressure (swelling). The accumulation of partial material damage and microcracking over time reduces the global safety of the member. More severe damage in concrete also changes the capillary pore structure (tortuosity, crack widths) and increases permeability parameters. Permeability of concrete is therefore an important performance value and its increase over time can indicate critical states.

Near-surface concrete has a higher capillary porosity compared to core concrete. Due to evaporation loss and autogeneous shrinkage the degree of hydration of near-surface concrete is lower and capillary pore sizes are higher compared to core concrete. Investigations on the durability of concrete have concentrated primarily on near-surface concrete, because the corrosion behaviour of reinforcement steel is influenced significantly by conditions in the top layer.

Permeability tests have proved to produce accurate and reliable information on the transport capacity of cement paste and concrete [1, 2]. Fluid and gaseous media have been used for permeability tests and their data show good correlation [3, 4]. Gaseous media are often preferred for permeability tests because they reduce testing times. In the following we therefore discuss concrete test methods based on air permeability.

Normally cylindrical specimens cut from drilling cores are being used in laboratory tests. No standard procedures are available so far for laboratory tests. Preconditioning and drying of samples is essential for comparable results [5, 6]. For air permeability tests steady state conditions at three different pressure levels up to 0.3 MPa have been recommended [7]. Bubble counters with relatively low accuracy are used for measuring the air flow rate. Other methods use a pressure decay technique and calculate intrinsic permeability from that [8].

Developing on-site permeability tests is highly important for being able to prove the quality of concrete. So far only the Torrent test [9, 10] has been standardized. Partly saturated concrete conditions represent a serious drawback of all on-site tests because these varying conditions complicate the interpretation of test results and lead to a scattering of permeability data. Many on-site methods are based on vacuum chambers [10, 11] working with declining pressures. Other methods use bore holes to apply a negative pressure [12, 13]. The three-dimensional flow field is often not clearly defined and neither the flow length nor the pressure gradient can be specified. In summary one can say that due to concrete humidity, three-dimensional flow fields and non-steady flow states (decay technique) it is difficult to define a proper permeability coefficient based on currently used on-site permeability tests. In the following article we present an analyzing method and a test setup for laboratory and on-site permeability measurements on concrete which overcomes some of the above mentioned problems.

2. AIR-PERMEABILITY TEST SETUP

At the MTI department of Innsbruck University a permeability test setup has been developed for laboratory and on-site usage. The measuring system consists of a pressure vessel with a control valve and pressure gauges, a permeability cell and an amplifier connected to a computer for data acquisition. For on-site applications the permeability cell can be replaced by a gasket disk fixed to the concrete by an injection packer of 30 mm diameter. A picture of the laboratory setup is shown in Fig. 1 and Fig. 2 presents the Packer setup.

The test specimens for laboratory tests were 20-30 mm thick disks cut from cores of 100 mm diameter. These samples were preconditioned by drying them at 105 °C. The specimens are fixed between two steel tubes (d=100 mm) and are inserted into the permeability cell. A rubber hose is used for lateral sealing of the specimen with air pressure.

The on-site tester is mounted in a 30 mm diameter hole drilled into the concrete where a packer will be lodged. The bore dust is collected for analysing the humidity and, if necessary, the chemical composition of the concrete. The packer is fixed in the hole in such a position as to leave an air gap just below the concrete surface. First experiments were performed with a

30 mm air gap, in later tests a gap of only 10 mm depth was used leading to better results. The surface is sealed with a rubber gasket disk pressed on to the concrete by an 80 mm diameter aluminium plate. The air pressure is applied to the hole gap via a connection hose fixed to the aluminium plate. The concrete surface may be pre-dried with hot air, ensuring, however, that the temperatures remain below 120 °C. Higher temperatures could already lead to micro damage in the concrete.

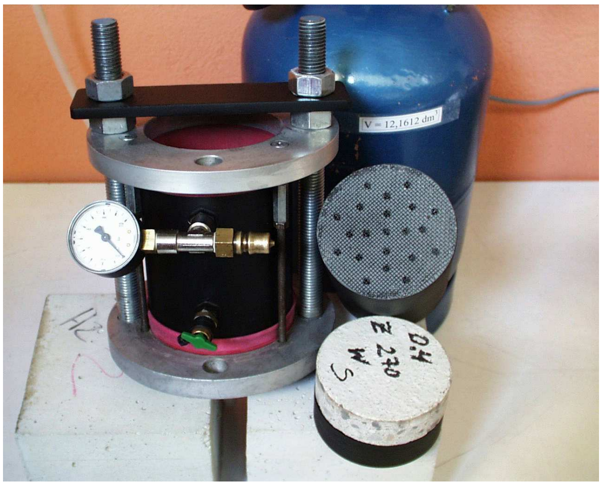

Fig. 1: Laboratory test setup (Disk test), the sample is not yet inserted in the cell
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Fig.2: On-site test setup (Packer test)

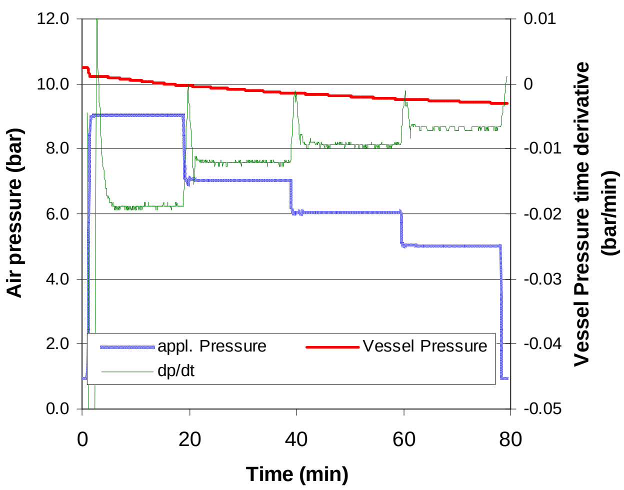

Fig.3: Typical plot of air permeability test data with four pressure steps

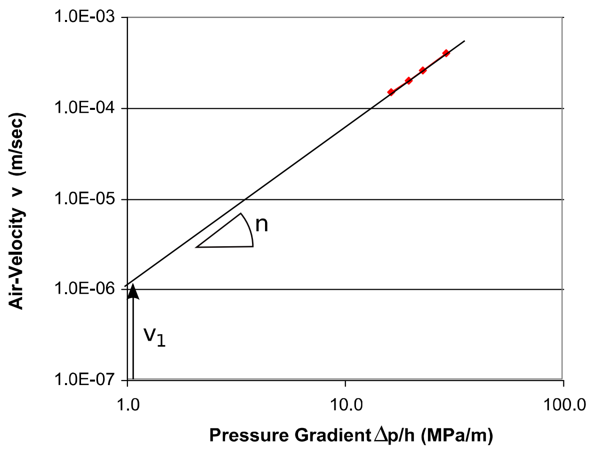

Fig.4: Data analysis applying the power law to the four pressure steps

The procedure for the permeability measurements is the same for both setups. The test begins by applying the highest air pressure level controlled manually by means of a valve. After reaching constant flow rates (steady state conditions) the conditions are kept constant for accuracy reasons as long as it takes for the vessel pressure to drop by more than 50 mbar.

The accuracy of the pressure gauge is in a range of 0,5-1 mbar which gives an accuracy better than 1-2% of the passing flow volume. A total of at least three different pressure steps are applied. The applied air pressure and the decreasing pressure in the vessel are measured in constant time steps for data analysis. A typical plot of test measurements is shown in Fig. 3.

3. AIR-PERMEABILITY PARAMETERS

The coefficient of permeability k_f relating to incompressible fluid media is calculated according to Darcy´s law

$$v = \frac{q}{A} = \frac{k_f}{\eta} \cdot \frac{\Delta p}{h} \tag{1}$$

where v is the flow velocity of the media (m/s), q is the mass flow (m^3/s), A the cross section area of the specimen (m^2), k_f the coefficient of permeability (m^2), η the dynamic viscosity (Pa.s), Δp the pressure difference (Pa) and h the flow length through the specimen (m). Equation (1) provides a linear relation between velocities and pressure gradient on the one hand and the material constants k_f and η on the other. For turbulent flow with high velocities and for viscous flow with low velocities the linear Darcy law cannot be applied. Additional inner forces in the fluid lead to nonlinear flow behaviour in liquids.

For compressible media like gases their compressibility must be considered. Applying gas law to Eq. (1) the coefficient of permeability k_g for gases in a one-directional flow field is given by [3, 7]

$$k_g = 2 \cdot \eta \cdot h \cdot \frac{q}{A} \cdot \frac{p_a}{p_i^2 - p_a^2} \tag{2}$$

where p_i denotes the applied gas pressure on the specimen and p_a the ambient air pressure. In a one-dimensional radially symmetrical plane flow field the coefficient of gas permeability k_r becomes

$$k_r = ln(\frac{d}{d_h}) \cdot \frac{q_a \cdot p_a \cdot \eta}{2 \cdot \pi \cdot h \cdot (p_i^2 - p_a^2)} \tag{3}$$

where d denotes the diameter of the gasket disk (m), d_h the diameter of the bore hole (m), q_a the volume flow rate of air (m/sec), h the depth of the air gap (m), p_i the applied air pressure on the sample (Pa) and p_a the ambient air pressure (Pa).

Concrete can have a very low coefficient of permeability (10^{-18} m^2 for liquids) in the range of dense rock (µD=10^{-6} Darcy). For such dense materials the conditions of linear Darcy flow do not exist. Many nonlinear models are known to describe non-Newtonian fluids like the power law model (Ostwald - de Waele), the Bingham model or the Hershel-Bulkley model. These models need at least two ore more material parameters to describe the flow behaviour.

It has been shown, that velocities and pressure gradients of air permeability tests can be displayed in a log-log plot in a nearly linear relation. This is shown in Fig. 4 for the measured test data of Fig. 3. On this basis a newly derived power law for gas transport in concrete has been proposed in Ref. [14-16]. Using two permeability parameters (v_1, n) the air velocity can be expressed as

$$v = v_1 \cdot \left[\frac{p_{abs}}{h} \right]^n \tag{4}$$

where v_1 is a reference velocity at a pressure gradient of 1 MPa/m, p_{abs} is the applied absolute air pressure, h is the air flow length and n is a permeability exponent. The exponent n can be obtained from any two test points (Eq. (5), u=upper, l=lower) which fit best the linear behaviour in Fig. 4.

$$n = \frac{-\ln(\frac{v_l}{v_u})}{\ln(\frac{p_u}{p_l})} \quad (5)$$

The permeability exponent *n* can be regarded as quantifying the capillary tortuosity, which in the case of Darcy conditions results in *n*=1. Turbulent flow can be expressed by *n*<1 and very slow laminar flow by *n*>2.

The flow field of Packer tests below the gasket disk is radially symmetrical, but near the edge the velocity vector turns sharply towards the concrete surface. Therefore, even under totally dry conditions, the coefficient of permeability calculated according to Eq. (3) is smaller compared to the one-dimensional coefficient of Eq. (2). In equations (4) and (5) the velocity has to be replaced by the volume flow rate *q* (m^3/sec) as for radial flow segments a constant flow rate define steady state conditions.

4. EXPERIMENTAL DATA

Air permeability tests were performed as part of a research program [14] involving concrete composed of two different cement types and water/cement ratios from 0.4 to 0.7. Samples were taken from the surface, the reinforcement and the central depth and exposed to water curing for 0, 1, 3 and 28 days. The test specimens were drilled from concrete blocks of 20 and 40 cm height. Test results and details of concrete mixes are published in Ref. [14] and partly in Ref. [15, 16]. All test data shown in the following figures are normalized for a cement content of 300 kg/m^3.

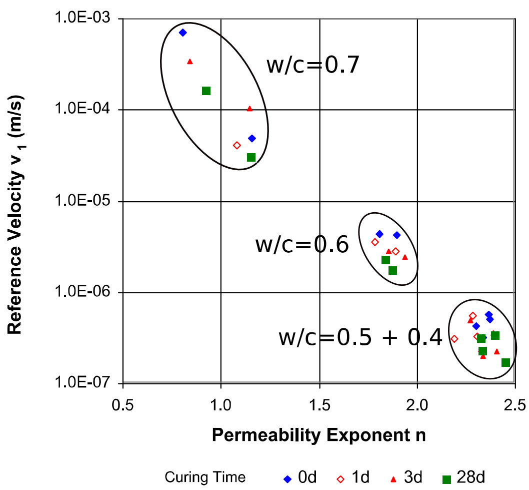

Fig. 5a: Influence of curing time and depth of specimen

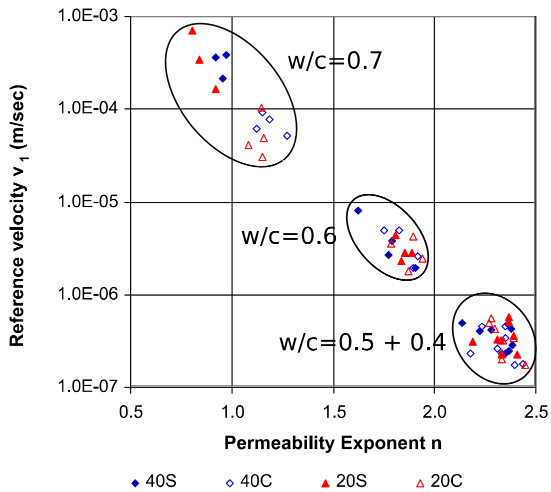

Fig.5 b: Influence of block height (20, 40 cm) and depth of specimen (S surface, C central)

Figures 5a and 5b show permeability parameters derived according to the power law (Eq. 4) for Disk tests on CEM II A-S 32.5R types of concrete with a Blaine value of 3400 cm^2/g. The different w/c-ranges are clearly distinguishable and the influence of curing time, block height or depth from the surface is indicated in a proper manner. For finer CEM I 42.5R (Blaine 4700 cm^2/g) types of concrete the w/c-ranges overlap partly but the relations in the different parameters still remain. Similar results were obtained using Eq. (2) to calculate the coefficient of permeability. The results are shown in Fig. 6 in relation to the capillary porosity which is another key value determining concrete permeability. The porosities of CEM I 42.5R concrete are slightly smaller than those of CEM II A-S 32.5R concrete, which is due to a higher degree of hydration for the finer cement type.

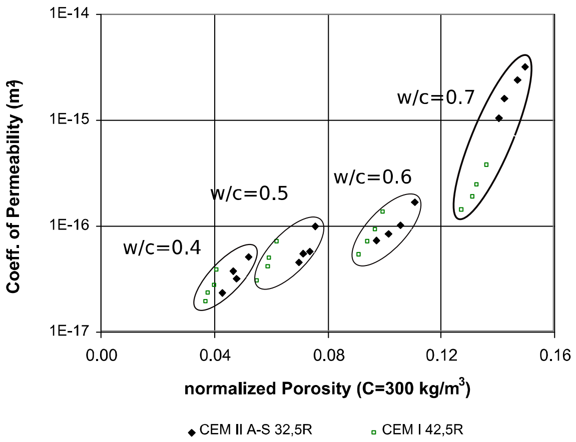

Fig. 6: Coefficient of permeability vs. capillary porosity in Disk tests

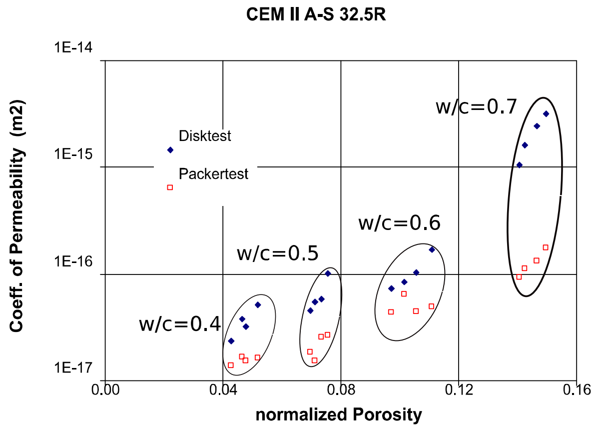

Fig. 7: Comparision of coefficients of permeability from Packertest vs. Disktest

A comparison of results shows that the full range of permeability coefficients spans 2.5 orders of magnitude, while the reference velocities v_1 cover 4 orders of magnitude. The analysis according to the power law results in two parameters (n, v_1), which both describe concrete transport properties.

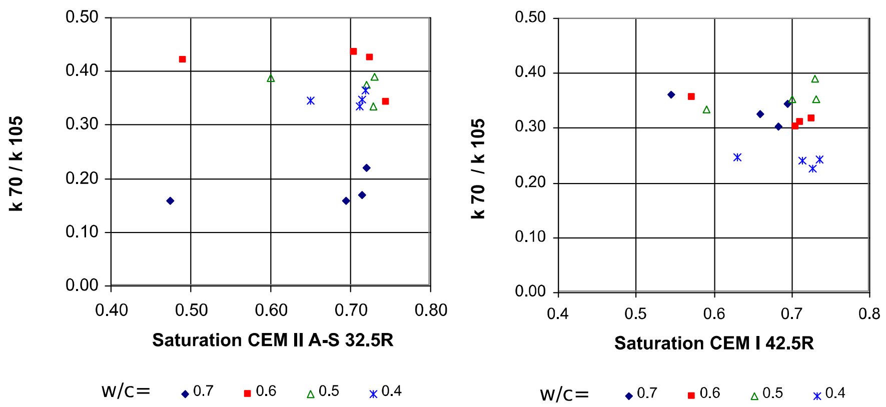

Fig. 8 a,b: Relative permeability coefficients (Disk test) of partly saturated specimens dried at 70 °C and at 105 °C respectively

Results of on-site permeability tests are difficult to evaluate due to the partial saturation of the capillary pore system. Preliminary Disk tests were performed with specimens (h=30 mm) which had been dried for 5 hours at 70 °C and were then compared with results obtained from the same specimens dried at 105 °C. The relative permeability coefficients calculated as a ratio $k_{70\,°C} / k_{105\,°C}$ are shown in Fig. 8a for concrete with CEM II A-S 32.5R and in Fig. 8b for concrete with CEM I 42.5R. Except for specimens which had not been water cured the range of saturation lay between 0.65-0.75. The relative permeability coefficients were comprised between 0.14-0.44.

Figures 9a and 9b show the permeability coefficients measured using the Packer test. The drying of concrete cubes was done under laboratory conditions (19<T<22 °C, 55%<rH.<65%) without any further surface drying prior to testing. Compared to the results from Disk tests the overall variation of data is smaller especially for w/c=0.7 concrete. However, the scatter of data for a fixed curing time (e.g. 3d) is higher compared to Disk test results [15]. That means that the accuracy of Packer test data is reduced compared to that of Disk tests. A comparison of Packer test and Disk test data for near surface specimens is given in Fig. 7.

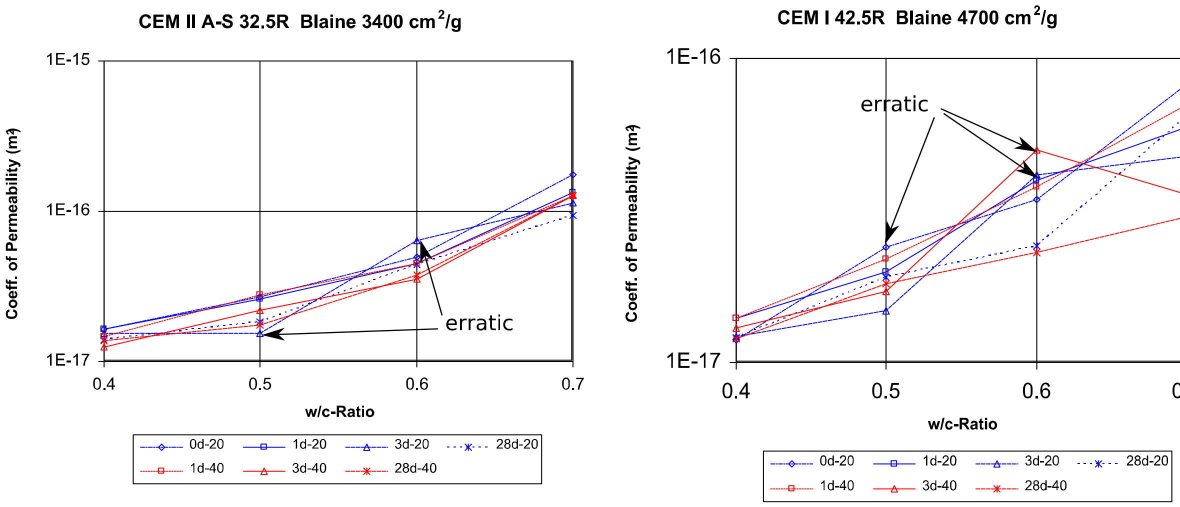

Fig 9 a,b: Packertest permeability data for concrete with different cement types, water cured for 0, 1, 3 and 28 days and block heights of 20 and 40 cm

5. CONCLUSION

This paper describes a laboratory and an on-site test setup for air permeability of concrete. The air flow volume rate is accurately measured with pressure gauges under steady state conditions. Key parameters for air permeability were obtained both according to the conventional flow law and based on a power flow law. These permeability data for concrete are spread over a range of up to four orders of magnitude; they constitute an accurate indication of concrete quality.

Due to the partial saturation of capillary pores the on-site permeability values are lower than those for dry laboratory tests. The ratio of permeability coefficients between laboratory and on-site tests have been found to vary by 2 to 18. Humidity conditions of on-site tests influence the permeability parameters much more than in capillary dry laboratory tests and may lead to erratic results. Additional measurements of concrete humidity and saturation can improve the interpretation of on-site permeability data.

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