AIR PERMEABILITY OF NEAR-SURFACE CONCRETE

PERMÉABILITÉ Á L`AIR DE BETON AU VOISINAGE DES SURFACE

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ABSTRACT – Concrete is exposed to a degradation mechanism mostly starting from surface planes. Near-surface concrete has often a reduced durability because of limited hydration. Reduced curing time, evaporation of capillary water and autogenous shrinkage leads to a higher transport efficiency of concrete close to a surface. The influence of curing conditions, mix design, porosity and cement type on concrete air permeability has been observed in a test programme. Key figures for air permeability were determined according to conventional recommendations and a newly formulated flow law. As a result of highly accurate permeability data of near-surface and core concrete pore structure, transport efficiency and curing conditions of concrete can be established.

RÉSUMÉ – *Les mécanismes de dégradation auxquels sont exposés les bétons s'initient généralement au niveau des parois. Le béton situé près des surfaces a souvent une durabilité réduite du fait d'une hydratation limitée. Un temps de cure réduit, l'évaporation de l'eau capillaire et le retrait d'autodessiccation conduisent à augmenter les phénomènes de transport dans les bétons au voisinage des parois. L'influence des conditions de cure, de la formulation, de la porosité et du type de ciment sur la perméabilité à l'air du béton a été étudiée au cours d'un programme expérimental. Les aspects clés concernant la perméabilité à l'air ont été déterminés selon les recommandations conventionnelles et une nouvelle loi d'écoulement. A partir de données de perméabilité très précises sur le béton de parois et en cœur, la structure porale, l'aptitude au transport et les conditions de cure du béton peuvent être établies.*

1. Introduction

Durability of concrete is an important aspect for economic use and amortisation of buildings. EN 206-1 and national standards contain a number of different exposition classes and the corresponding concrete properties necessary to resist different climatic, thermal and chemical environments. In order to comply with these exposure classes the standards define requirements on concrete mix design like maximum water cement ratio, cement proportions and cement type. The limitation of the w/c-ratio aims to reduce the capillary pore space. Requirements on pore size distribution or on the transport capacity of concrete (permeability) are generally not included in standards for concrete quality.

The deterioration of concrete usually involves movement of aggressive water solutions or gases from a surrounding environment through a concrete surface. Due to evaporation and insufficient hydration, near-surface concrete has higher porosities and coarser pore systems than core concrete. Therefore, the effect of deterioration processes on near-surface concrete is more pronounced. High ion concentration, high degree of carbonisation, strong thermal influence with large amplitudes of frost and humidity result in premature damage of near-surface concrete. Permeation and transport properties of concrete therefore give important evidence on concrete durability.

The transport capacity of concrete for gases and solutions is defined by a high inner surface with a fine pore size distribution of CSH gel. Mix design, curing time and type of cement in use can significantly influence the pore system and total porosity. Methods of analysis like BET or MIP differ strongly in their absolute values and need a highly equipped laboratory. On the other hand permeability provides a simple but still accurate method of describing the inner structure and transport capacity of concrete. Laboratory methods for air permeability rely on stepwise pressure increments in a linear flow cell on preconditioned specimen (RILEM, 1999) or (Gräf and Grube, 1986-88). On-Site methods are mostly based on vacuum systems with unsteady air flow, undefined humidity conditions and three-dimensional flow geometry (Figg 1973) and (Torrent, 1992). The variation of on-site permeability data is generally higher than that of laboratory data obtained under defined conditions.

Durability of near-surface concrete has been studied often and with different methods (Basheer and Nolan, 2001), (Dhir et al, 1987) (Parrott, 1995) or (Jacobs and Hunkeler, 2006). These studies show a strong influence of curing time, humidity and temperature on near-surface concrete. In this paper results of an extended laboratory test series on air permeability of concrete are presented. Concrete specimen have been produced with two cement types using w/c-ratios between 0.4 – 0.7. Curing time and depth of the specimen in relation to the surface were varied. Different humidity conditions from partially dry to totally capillary dry were used in specimen preparation. Key figures for permeability were calculated based on RILEM recommendations as well as on a newly proposed flow law.

2. Permeability

Analysis of transport capacity of concrete has been performed with fluid and gaseous media. Due to their low viscosity, gases are especially suitable for short and accurate measurements. Inert gases like O_2 or N_2 as well as plain air have been used for permeability tests on concrete.

For the calculation of permeability with fluid media Darcy's law is used in the form

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

where v is the flow velocity of the media (m/s), q is the mass flow (m^3/s), A the specimen area (m^2), k_f the permeability constant for fluids (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 velocity and pressure gradient with the material constants k_f and η. The test is performed under steady flow conditions.

For gaseous media the permeability constant k_g is obtained considering the compressibility of gas and applying gas laws (RILEM, 1999) to

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

where p_i is the applied gas pressure on the specimen and p_a is the air pressure. In general the air pressure can be assumed to app. 1 bar (10^5 Pa). Because of the validity of gas laws pressure has to be used in absolute terms.

Equation (3) is often applied to describe the relation between fluid and gas permeability constants (Klinkenberg, 1941) or (Claisse et al, 2003).

$$k_f = \frac{k_g}{1 + \frac{b}{p_m}} \tag{3}$$

Here k_g is the intrinsic permeability constant and p_m a mean gas pressure in the specimen. The material parameter b is influenced by the pore size distribution and is chosen for concrete with $b = 1.635 \cdot 10^{-8} \cdot k_f^{-0,5227}$ (Bamforth, 1987).

3. Experimental work

Air permeability of concrete has been tested in a research programme (Nasution, 2006). Concrete mixes with w/c-ratios from 0.4 to 0.7 were used with two different cement types , Cem II A-S 32.5R (Blaine 3400 g/cm^2) and Cem I 42.5 R (Blaine 4700 g/cm^2). Concrete mixes were designed for high cement proportions and are given in table 1.

Table 1, Concrete Mixes

Material	w/c = 0.4 kg/m^3	w/c = 0.5 kg/m^3	w/c = 0.6 kg/m^3	w/c = 0.7 kg/m^3
Cem II A-S 32.5R	685	600	427	390
Water	274	300	256	273
Quartz sand	787	787	944	944
Quartz agg.	524	524	629	629
Cem I 42.5R	700	610	440	390
Water	280	305	264	273
Quartz sand	787	787	944	944
Quartz agg.	524	524	629	629

Concrete cubes (20 cm) were produced and then water cured for different periods. After 28 days 100 mm diameter cores were drilled out of the cubes and cut into 30 mm thick disks. These specimens were taken from three different depths (0-30 mm, 30-60 mm and from core concrete) for testing air permeability. They were first dried for 5 hours at 70 ^{o}C and than tested in a partially saturated state. Then they were dried at 105 ^{o}C to reach capillary dry conditions and tested again at around 32 days after mixing. Porosity and saturation have been measured as the mass difference between water saturated and dried specimen.

Four storage systems have been applied simulating different curing conditions.

- air curing under laboratory conditions at 55-65 % r.H.
- 1 day wet storage
- 1 day wet and 2 days underwater storage
- 1 day wet and 27 days underwater storage

For permeability testing a specially developed flow cell with an overpressure vessel was used (Fig.1). The applied pressure could be regulated by a control valve. The flow volume was calculated from the pressure drop in the vessel. The side sealing of specimen was achieved by exposing it to a confining pressure higher than the applied pressure. Flow data for calculating the air permeability were recorded between steady flow states. A typical pressure – time plot is given in Fig. 2.

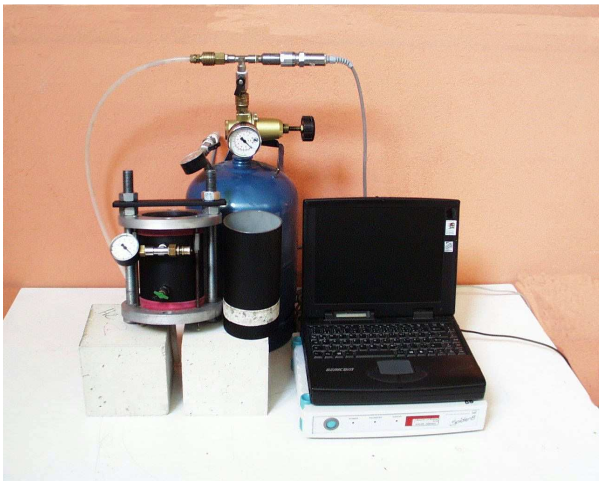

Figure 1, Permeability air flow cell

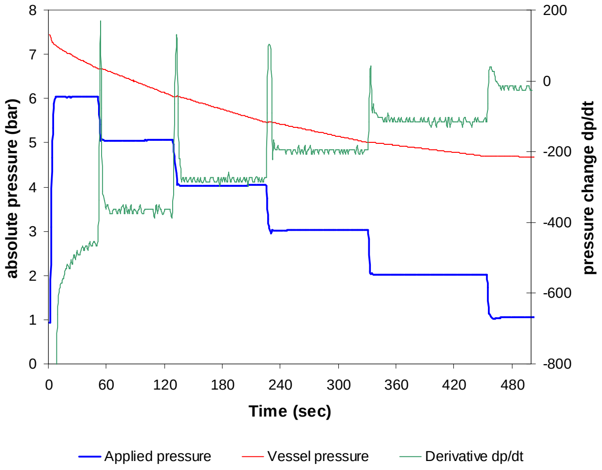

Figure 2, Pressure step plot, w/c=0.7

The applied pressure was varied in a stepwise fashion. The maximum air pressure was applied dependent on the density of concrete in a range of 5-9 bars with a maximum pressure gradient around 20 MPa/m and 3 to 4 times higher than recommended in (RILEM, 1999).

4. Air permeability constant of concrete

The determination and presentation of air permeability constant *k* is based on Eq. (2). In order to compare concrete mixes with different cement proportions the data have been normalized linearly to a cement proportion of 300 kg/m^3. The data presented here relate only to specimen dried at 105 ^{o}C to capillary-dry conditions.

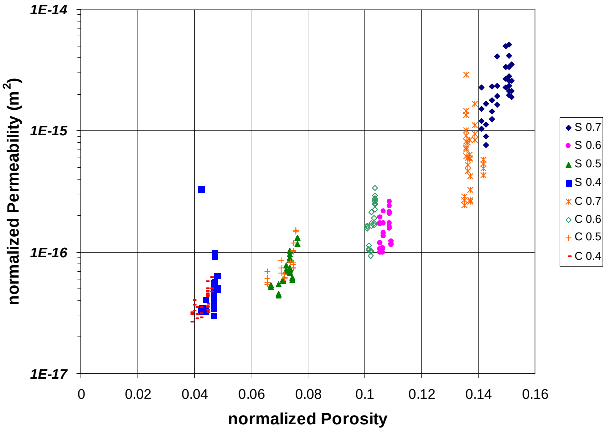

Figure 3, Permeability of Cem II A-S 32.5R concrete

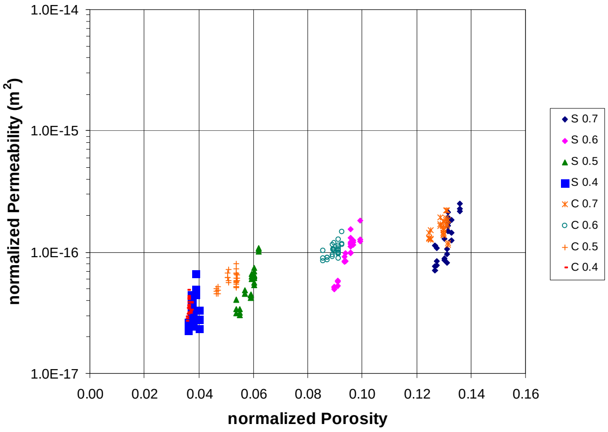

Figure 4, Permeability of Cem I 42.5R concrete

Figures 3 and 4 show permeability constants of concrete made with the two cement types and cured for all mentioned conditions. A comparison is made between near-surface concrete (S) and core concrete (C) for the four w/c groups. Clearly the different w/c groups are separated by porosity. Because of a higher degree of hydration, the finer Cem I 42.5R concrete always has a lower porosity (appr. 1%) than Cem II A-S 32.5R concrete. In general the core concrete permeability is between 2 to 5 times lower than that of surface concrete, except for the concrete with the Cem II A-S 32.5R made with a w/c ratio of 0.7 . For fine ground cement Cem I 42.5R the variation in permeability over the full w/c-range of 0.4 - 0.7 varies by a factor of 10 while for the coarse Cem II A-S 32.5R it varies by a factor of more than 100.

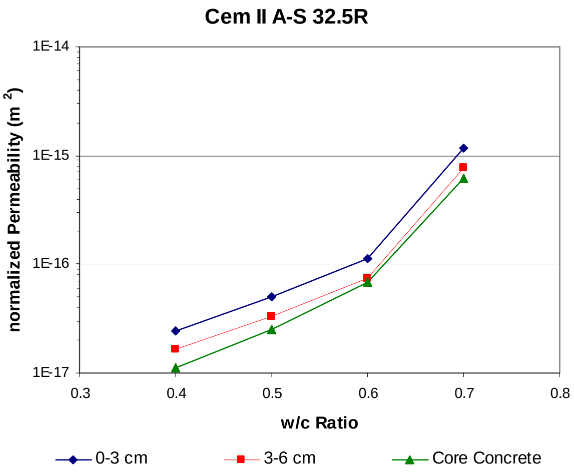

Figure 5, Surface distance influence on concrete permeability

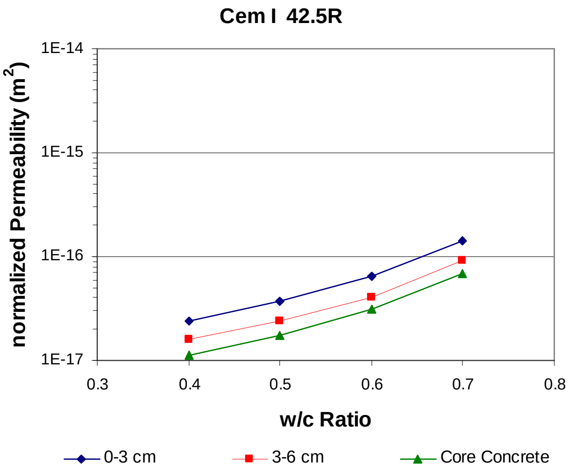

Figure 6, Surface distance influence on concrete permeability

The distance from the surface has a stronger influence on concrete permeability for higher w/c ratios. Figures 5 and 6 present the data obtained for concrete made with both types of cement and for a water curing period of three days. With a low w/c ratio of 0.4 the permeability of near-surface concrete is doubled compared to core concrete while with a w/c ratio of 0.7 it varied by a factor of up to 5.

The influence of curing time on permeability of near-surface concrete is presented in Fig. 7 and 8. The data show a variation of a factor of 2 to 3 for Cem II A-S 32.5R with decreasing curing times. A slightly higher sensitivity to curing is noticed for the finer Cem I 42.5R.

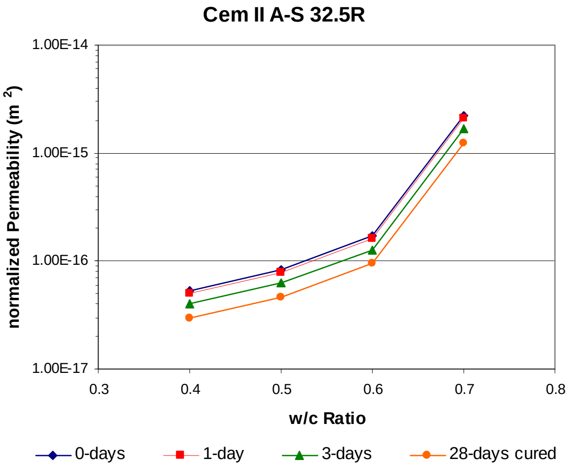

Figure 7, Curing influence on near- surface concrete permeability 0-3 cm

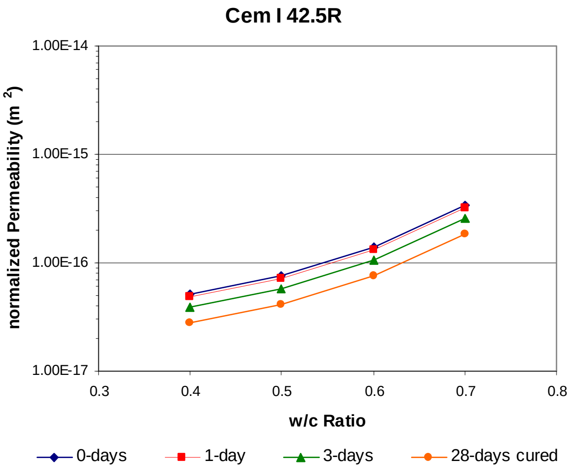

Figure 8, Curing influence on near-surface concrete permeability

5. Exponential flow law

There are some advantages to measuring air permeability at several different pressure levels especially materials of small capillary sizes. Not only can incorrect data be found and eliminated but a direct relation can be obtained between flow velocity and pressure gradient. Higher pressure levels give rise also to shorter measurement times.

Relating the air flow velocity to the pressure gradient leads to diverse functional relationships in concrete. For high w/c ratios around 0.7 a linear (Darcy) relation was found. The lower the w/c ratio or the denser the pore structure in the material, the more an exponential functional relation becomes dominant. This is shown in Figure 9 for a near-surface concrete with Cem II A-S 32.5R, one day wet cured, where flow velocities vs. pressure gradients are compared. Obviously neither Eq. (1) nor Eq. (2) covers the full range of concrete pore structures.

Figure 10 shows the same data as Fig. 9 in a log-log scale. A nearly linear relation seems to exist in this scale. Therefore a flow law as represented in Eq. (4) is proposed for low velocity air flow in concrete.

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

Therein v_1 represents an exit velocity (m/s) of air for a reference state. The permeability exponent n can be calculated using Eq. (5).

$$n = \frac{\ln\left(v / v_1\right)}{\ln\left(p_{abs} / p_1\right)} = \frac{\ln\left(v_u / v_l\right)}{\ln\left(p_u / p_l\right)} \tag{5}$$

A pressure gradient with $p_1/h = 1$ Mpa/m has been chosen as a reference state. Absolute air pressure data must be used. The exponent n can be calculated from upper (*u*) and lower (*l*) test data according to Eq. (5). The reference velocity v_1 is then obtained from any test data (p_{abs},v) using Eq. (4). Darcy conditions exist for $n = 1$.

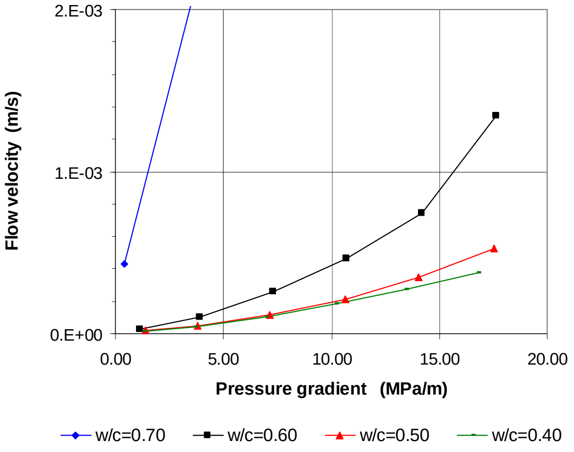

Figure 9, Linear velocity – pressure gradient plot

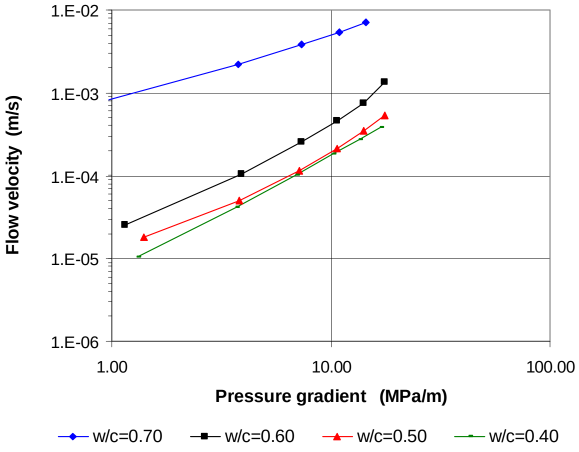

Figure 10, Logarithmic velocity – pressure gradient plot

The analysis of permeability tests according to Eq. (4) and (5) is shown in Figure 11 and 12. For the Cem II A-S 32.5R concrete the different w/c groups are separated quite clearly in an n – v_1 diagram. The data clouds are situated in a straight relation. Permeability exponents *n* around 1 were found with this cement at a w/c ratio of 0.7 and increased up to 2.4 with declining w/c ratios. Figure 12 presents the comparison between concretes for both cement types. Still the linear tendency can be seen but data of w/c groups overlap with finer ground cement Cem I 42.5R. A remarkably drop of the reference velocity occurs for this cement for concrete made with w/c ratio of 0.7 .

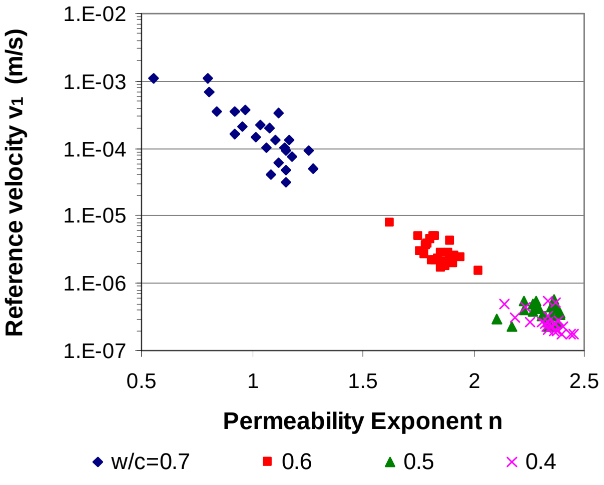

Figure 11, Cem II A-S 32.5 concrete

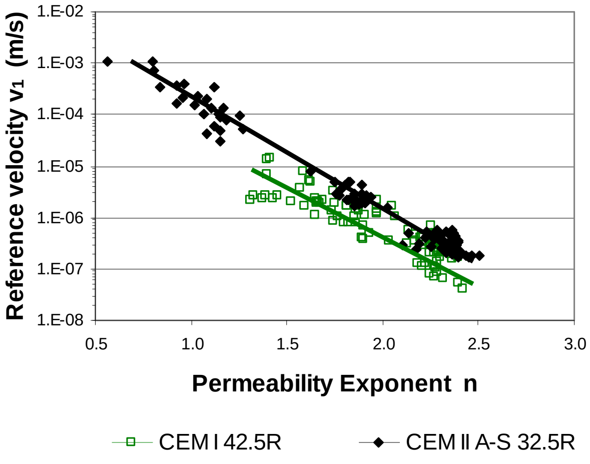

Figure 12, Comparisons of both cements

A proposal of a classification of concrete based on the reference velocity v_1 and the permeability exponent *n* is given in Table 2. These values were obtained from near-surface concrete 0-30 mm.

Table 2, Classification of air permeability of concrete

Permeability	Exponent n	Reference velocity v_1 (m/sec)
high permeable	< 1	$> 10^{-4}$
permeable	1 – 1.5	$10^{-5} – 10^{-4}$
low permeable	1.5 – 2	$10^{-6} – 10^{-5}$
very low permeable	> 2	$< 10^{-6}$

6. Conclusion

In order to achieve different exposition classes European and national standards define for concrete maximum w/c ratios, minimum cement proportion and cement type. It has been shown in a test program on air permeability of concrete, that besides w/c ratio also the curing time and the fineness of the binder influence significantly the pore structure and the transport capacity of concrete.

Air permeability has been measured on capillary-dry specimen under constant air pressure conditions up to 9 bars. The analysis of the data was based on the conventional permeability constant as well as on a newly proposed exponential flow law. Accordingly, permeability was characterized by two key figures which were used for evaluating concrete quality.

Air permeability of concrete can be measured highly accurate. Key figures describing air permeability vary over a few logarithmic decades. The transport capacity and durability properties of concrete can be evaluated properly on this basis.

7. References

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