# Air permeability as a characteristic parameter for the quality of cover concrete

Frank Jacobs & Fritz Hunkeler

**Abstract**

Many defects and non-conformities of concrete structures can be related to the planning and manufacturing process. The quality control on separately manufactured specimens or on structural members of a structure allows the early detection of non-conformities. If any, mainly destructive tests on the structure are carried out nowadays: compressive strength and/or tightness of concrete are determined on cores taken from the structural member. Non-destructive tests have existed for a long time, but are rarely used. In the framework of a research project it was aimed at to test the practical applicability of non-destructive air permeability measurement, carried out according to the Swiss standard SIA 262/1, annex E. To reach this goal, comprehensive investigations were carried out in the laboratory and on structures.

The investigations on structural members led to the conclusions that air permeability measurement is applicable with the following restrictions:

- Temperature: Air and concrete temperature should be > 5 °C.
- Moisture content: The specific electrical resistivity should be > 10 - 20 kΩcm or the moisture content, determined by capacity measurements, < 5.5 - 6.0 M-%.
- Age: At the time of measurement young concrete should have an age between approximately 1 - 2 months and approximately 1.5 years.

Instructions for planning, tendering and the execution of permeability measurements and the evaluation of the results according to the Swiss standard SIA 262/1, annex E, are detailed. Based on the experience the air permeability measurement can be recommended as a non-destructive method to determine the quality, i.e. the impermeability, of the cover concrete. It was found that air permeability is an indicator for durability properties like chloride migration coefficient, carbonation progress and capillary suction of water.

**Keywords:** air permeability, durability, non-destructive testing, quality control

Frank Jacobs, studied geology at University of Erlangen/Nuremberg, Germany, PhD at ETH Zürich, Switzerland, on permeability of concrete. Senior consultant at TFB (Technical Research and Consulting on Cement and Concrete) in Wildegg, Switzerland. Working mainly in the field of concrete technology including self compacting concrete, durability and environmental impact of concrete. Engaged in national and international working groups.
Fritz Hunkeler, studied materials sciences, PhD at ETH Zürich, Switzerland. Director and senior consultant at TFB in Wildegg, Switzerland. Working mainly in the field of durability, assessment and rehabilitation of reinforced concrete structures. Engaged in national and international working groups.

## INTRODUCTION

Over the last two decades it has been recognised that most damage to reinforced concrete structures has been caused by insufficient durability and not to low strength. The quality and thickness of the cover concrete determines in most cases the durability. The properties of the cover concrete are not solely determined by the concrete mix, but also by the pouring, compaction and curing of the concrete. Matousek et al. [1] made an analysis of 800 cases of insurance companies in the field of construction work. 44 % percent of all cases and 72 % of the loss of money can be attributed to deficient actions on the structure. 37 % of all cases were caused by mistakes during the planning and 35 % during the execution process. With an appropriate quality control system during execution 1/5 of all cases with damage could have been detected and prevented. Part of the avoidable cases can be attributed to insufficient concrete quality.

The quality of concrete with respect to durability should be investigated on the structural member because separately manufactured samples differ in compaction and curing. Ideally, investigations on structural members should preferably be non-destructive and carried out at an early age when no severe damage is present. If cores are taken, compressive strength (SN EN 12504-1) with an assessment according to SN EN 13791 or capillary suction (SIA 262/1, annex A) can be determined. Various non-destructive methods, e.g. rebound number (SN EN 12504-2), ultrasonic pulse velocity (SN EN 12504-4) or air permeability (SIA 262/1, annex E), can be applied. Generally the quality of finished concrete structures is usually only determined in cases where the quality is doubtful. This can partly be explained by the wish of the owner not to damage the structural member and the lack of standard non-destructive tests for durability with meaningful results.

In two earlier research projects non-destructive permeability methods (Figg, ISAT, Schönlin, TUD, specific electrical resistivity, etc.) were investigated mainly in the laboratory but also on-site (Torrent & Ebensperger 1993 [2], Torrent & Frenzer 1995 [3]). The determination of the air permeability according to Torrent (TPT) seemed to be a promising method for the evaluation of durability. The authors concluded from their studies that the method should be tested in the field.

In the last years the RILEM working group "Non Destructive Evaluation of Cover Concrete" (NEC RILEM TC 189) examined different methods to determine the permeability of the cover concrete of concrete structures [4]. The air permeability, determined with the TPT, proved to be a suitable method. It allowed the correct assessment of the concrete quality in six out of seven test conditions (different concrete types, storage conditions and temperatures). Additionally, a small scatter of the results was observed and the method was relatively fast and non destructive.

## INVESTIGATIONS

Within a four year research project at TFB the basis for the application of the air permeability measurements according to SIA 262/1, annex E (TPT), as well as the evaluation of the results have been clarified. The investigations were carried out in the laboratory as well on approximately 60 young (< 5 years old) and 30 older (20 - 40 years) structural members. The results are given in [5]. This paper contains a summary of the results of the measurements on structural members.

## AIR PERMEABILITY ACCORDING TO SIA 262/1, ANNEX E

### Method

In a test chamber (∅ = 4 cm) and a "guard ring" surrounding the test chamber (Fig. 1), both open to the concrete surface, a vacuum of approximately 10 - 20 mbar is applied via a vacuum pump. After the pump is stopped in the measuring chamber, air flows from the concrete into the chambers. The more porous the concrete is, the more air flows into the chambers. In the test chamber the pressure build-up is measured as a function of the time, starting at the time $t_o$ (completion of the evacuation of the measuring chamber). From the pressure change and further characteristics the air permeability is calculated. The "guard ring" is necessary to achieve a linear air flow into the test chamber (see arrows in Fig. 1).

Air permeability is calculated according to the following equation (Torrent & Frenzer [3]):

$$k_T = \left(\frac{V_c}{A}\right)^2 \frac{\mu}{2\varepsilon p_a} \left( \frac{\ln\left( \frac{p_a + p}{p_a - p} \frac{p_a - p_o}{p_a + p_o} \right)}{\sqrt{t} - \sqrt{t_o}} \right)^2$$

kT: air permeability [m$^2$]
$V_c$: volume of the test chamber [m$^3$]
A: cross section area of the test chamber [m$^2$]
µ: dynamic viscosity of air [Ns/m$^2$]
ε: porosity of concrete [-], assumed as constant: 0.15
$p_a$: air pressure [N/m$^2$]
$p_o$: air pressure at time $t_o$ (start of the measurement, after evacuation) in the test chamber [N/m$^2$]
p: pressure at time t (end of the measurement) in the test chamber [N/m$^2$]

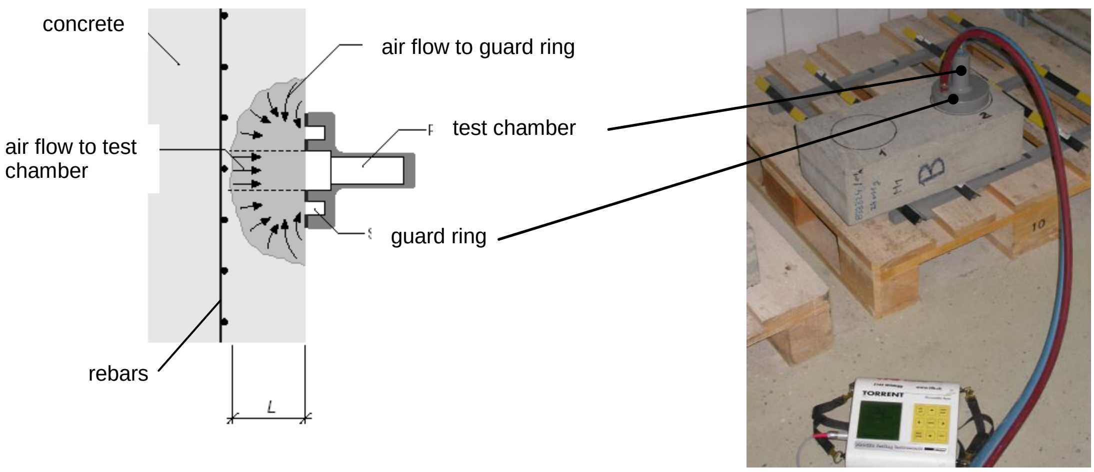


**Fig. 1: Left: sketch of the principle of the TPT-method (from SIA 262/1); right: measuring device on concrete specimen.**

The air pressure in the test chamber after the evacuation is partly in the range of the water vapour pressure (Romer [6]); i.e. with such a low pressure, water can evaporate from the concrete pores until the appropriate water vapour pressure for a given temperature (fig. 2) is attained. Apart from the temperature, the water vapour pressure is also affected by the composition (type and quantity of salts) of the pore water in the concrete. Thus, if wet concrete is measured the increase in pressure in the test chamber is caused by two processes:

- evaporating water from the concrete pores
- air flow from the concrete pores.

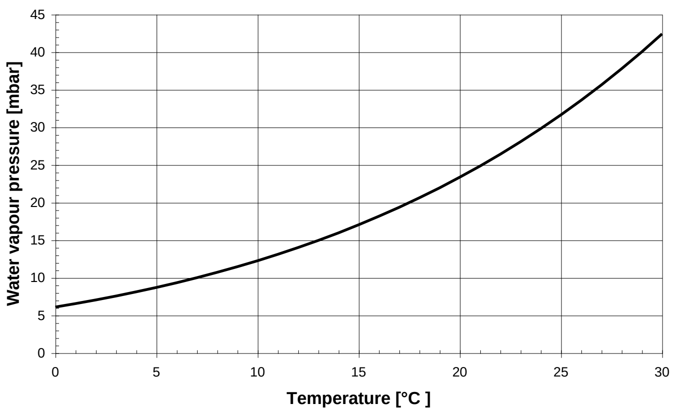


**Fig. 2: Water vapour pressure as function of temperature; data taken from Handbook of Chemistry and Physics.**

### *Evaluation of data*

Air permeabilities measured on structural members show a mono- to multimodal distribution and can vary over more than one order of magnitude (Fig. 3). In order to limit the influence of a few very high or very low measured values on the calculated representative air permeability, the arithmetic mean of the logarithmised measured values (= geometrical mean of the measured values) is used (Fig. 4). The geometrical mean is clearly less sensitive to extreme values than other average values (median, arithmetic mean of the measured values).

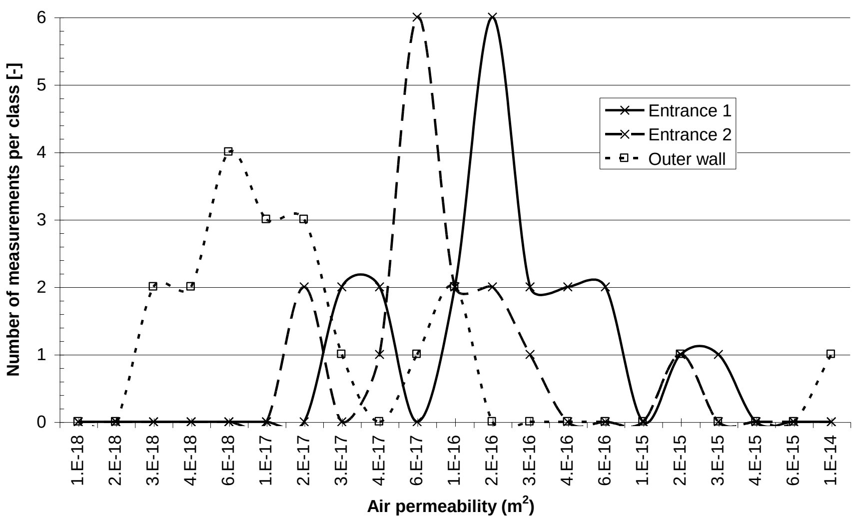


**Fig. 3: Distribution of air permeability values, determined on various structural members**.

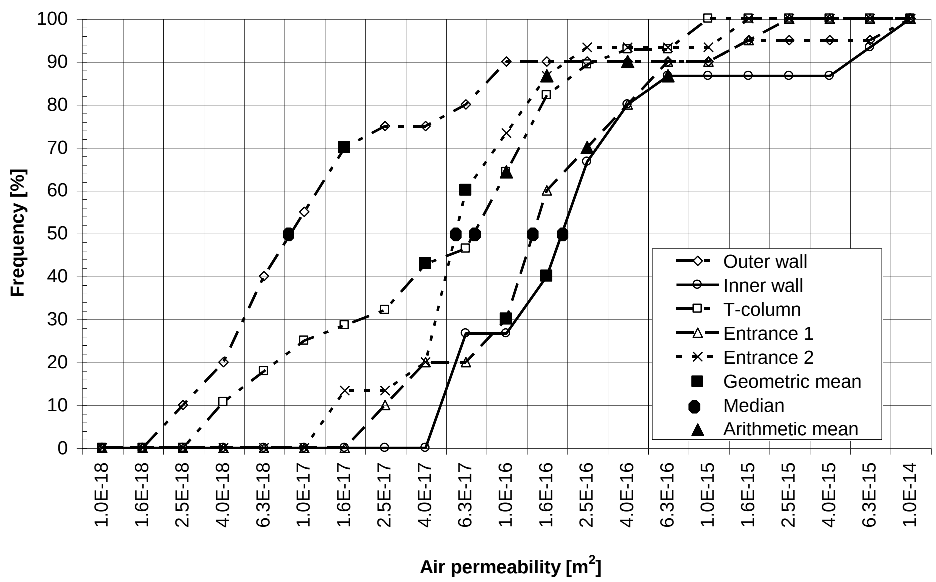


**Fig. 4: Cumulative frequency of air permeability values of different construction units; several mean values are marked: median, arithmetic geometric mean).**

As evident from Fig. 4, the scatter of the measured values can be rather large, even for a single structural member. Causes for this might be e.g. microcracks, roughness of the concrete surface leading to very small leakages and concrete inhomogeneities. It is assumed that the maxima at relatively low permeabilities are representative for the concrete and that the rather high permeabilities are a sign of e.g. microcracks. Usually extreme values are at least a factor of 5 - 10 higher than the geometrical mean of all measurements made at one structural member. If the extreme values are not considered in the analysis, the geometrical mean is hardly and the standard deviation more strongly affected. Calculating the standard deviation with and without exterme values gives an indication of the scatter of the data.

## RESULTS

For each of the 58 structural members with an age of less than 5 years between 3 and 30 air permeability measurements were made. The air permeabilities of the structural members lay mostly between 0.02 and $2 \cdot 10^{-16}$ $m^2$. The air permeabilities measured by Torrent & Frenzer [3] are comparable. Air permeabilities measured in the Munich stadium (Kubens et al. [7]) are comparatively very low. It may be that the concrete was rather wet, which can lead to a low air permeability. In Fig. 5 the air permeability is plotted against the standard deviation. No relationship can be seen. The arithmetic mean of the standard deviation is 0.34 $m^2$ and the lowest 75 % percent of the standard deviation is less than 0.48 $m^2$. The construction of tunnel 6 lasted approximately two years. At the time of the air permeability measurements, the age of the concrete ranged between 5 and 29 months. The standard deviation of all investigated structural members is 0.43 $m^2$. Therefore, it can be expected that for homogeneous structural members a maximum standard deviation of approximately 0.4 $m^2$ can be achieved.

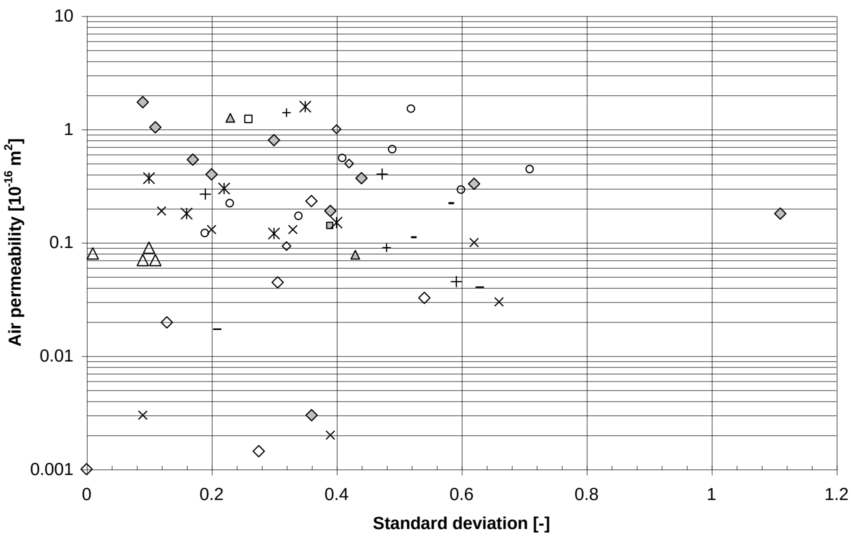


**Fig. 5: Mean air permeability versus standard deviation calculated without the extreme values**

**Influence of moisture content and temperature on air permeability**

Between the air permeability and the specific electrical resistivity (measure for the moisture content of concrete) (Fig. 6), or the moisture content determined by a capacity method only a weak relationship was found. The lowest air permeability was determined on concrete with a specific electrical resistivity of less than 20 kΩcm or a moisture content of more than 6 M.-%. Between concrete mixes with and without pozzolanic additions no clear differences was seen, although concrete with pozzolanic additions should have a higher specific resistivity. A substantial reason for this lies in the fact that different structural members with different w/c-ratios and different moisture contents are compared. This could mask the influence of pozzolanic additions. If structural members with and without pozzolanic additions and with identical exposition (e.g. tunnel 1) are compared a difference of about a factor 2 of the specific electrical resistivity was found, which can be expected.

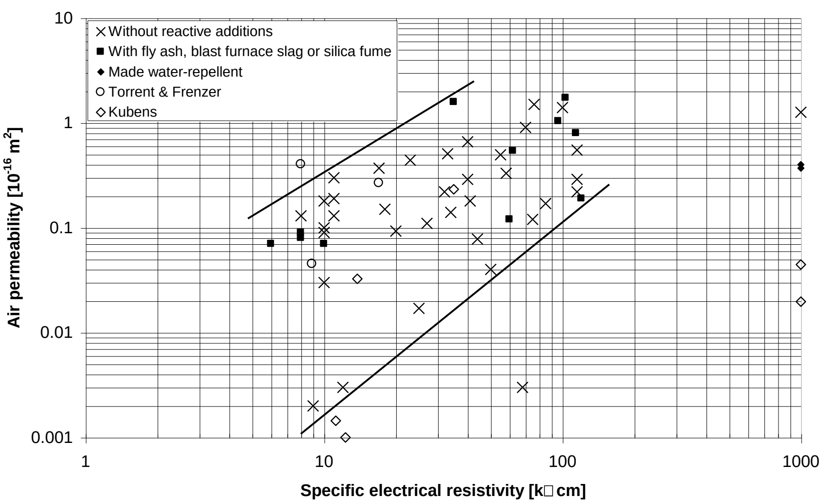


**Fig. 6: Mean air permeability (without extreme values) as function of specific electrical resistivity**

No relationship between the air temperature and the measured air permeability was identified, i.e. the influence of the temperature is not masking other influences and the scatter. This is in accordance with the results of laboratory tests which were made in the temperature range between 5 and 20 °C. On average an increase in air permeability of 15 to 30 % was found when temperature was increased from 5 to 20 °C.

**Air permeability and w/c-ratio**

Data from concrete quality control for most of the examined structural members were available. In Fig. 7 air permeability is plotted against the w/c- or the w/$c_{eq}$-ratio. A large scatter is remarkable at a w/c-ratio of 0.50. No significant influence of air content or content of pozzolanic additions was observed. Concrete containing Portland limestone cement (CEM II/A-LL) showed a rather high air permeability in some instances. This was confirmed in the laboratory investigations.

The solid line in Fig. 7 corresponds to the mean relationship between air permeability and w/c-ratio; the mathematical equation is given in the legend of this figure. A similar relationship was found in the investigations in the laboratory as well as CEB [8]) and Jacobs [9]. CEB and Jacobs determined the permeability with the Cembureau method. Air permeability measurements on rather "wet" concrete components (filled symbols in Fig. 7, specific electrical resitivity less than 20 kΩcm) differ only partly from the other measured results. Measurements carried out at temperatures of less than 4 °C are shifted to very low air permeability.

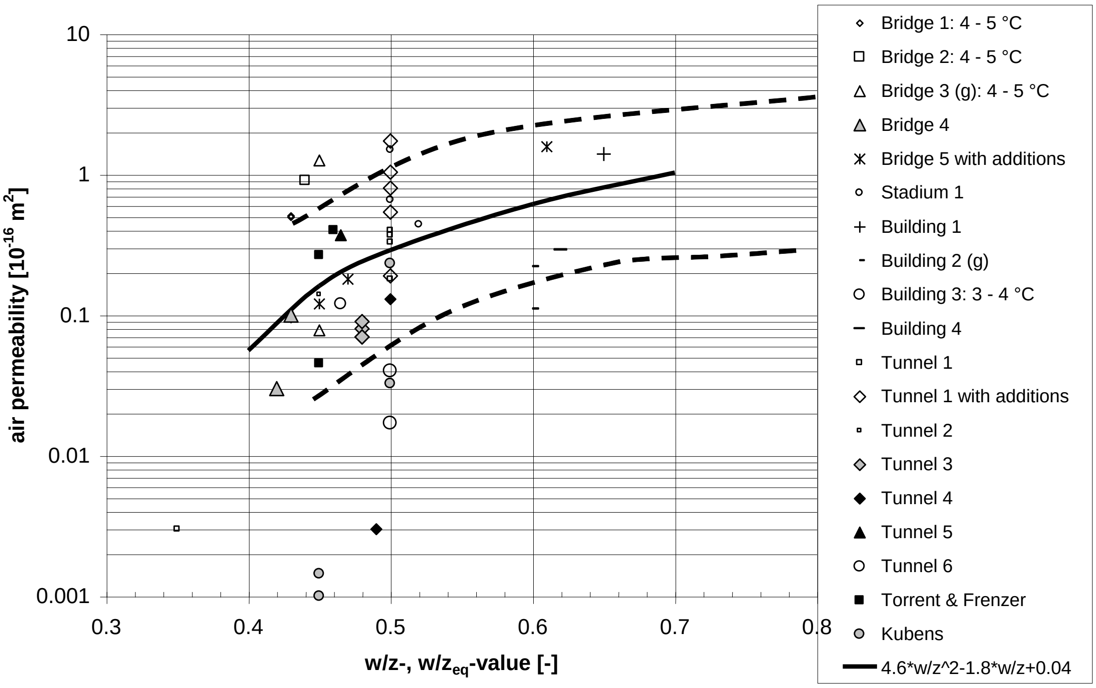


**Fig 7: Air permeability and w/c ratio; filled symbols: resistivity < 20 kΩcm; (g): w/c estimated from compressive strength. Air temperatures less than 5 °C are indicated in the legend.**

The rather high scatter of air permeability at the same w/c ratios can be interpreted by the well known fact that the w/c ratio is not the only parameter determining the impermeability of concrete. Other important influences might be for instance:

- influence of type of cement and pozzolanic additions
- different temperatures during hardening of the concrete
- curing of concrete
- scatter in the determination of the w/c-ratio (ca. ± 0.02)
- inhomogenities in concrete due to e.g. compaction

A further analysis of the data showed that the majority of the values above the bold line are due to particular reasons for example:

- air temperature ≤ 5 °C
- use of pozzolanic additions
- high moisture content (< 20 kΩcm)

## Air permeability and other concrete properties

A loose relationship between the 28 day cube compressive strength and the air permeability, measured after several months can be observed (Fig. 8). The influence of the change in air permeability with time (28 days → several months to a few years) was not considered. The loose relationship is well known from earlier investigations (e.g. [9]) and can be attributed to the fact that on the one hand the compressive strength is determined on 150 mm cubes while the air permeability is determined on the outer 1 - 2 cm of the structural member and on the other hand that both concrete properties depend not equally on the pores size distribution. The data of Torrent & Frenzer [3] lie in the range of the own investigations while those of Kubens et al. [7] are partly lower, which can be attributed to a high moisture content of the concrete. The relationship from Bakhshi et al. [10] is shifted to higher air permeabilities. This might be explained partly by the storage conditions: The concrete samples were stored for 2.5 years at 65 % r.F. [10] which results in a much lower moisture content and thus in a higher gas permeability.

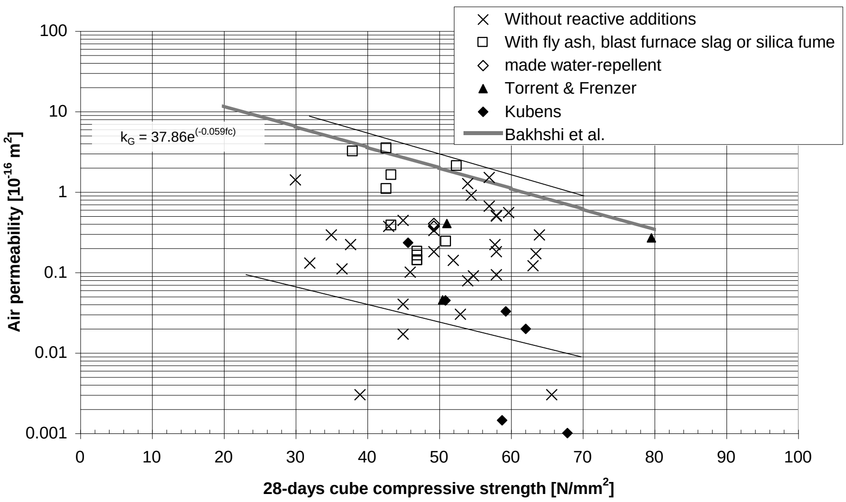


**Fig. 8: Mean air permeability (without extreme values) as function of the 28 days compressive strength; additionally the relationship from Bakhshi et al. [10] for laboratory concrete is shown.**

On older concrete structures (20 - 40 years old) the carbonation depth (determined with phenolphtalein), the chloride penetration (acid soluble chloride content) and air permeability were determined. Between the minimum, middle or maximum carbonation depth and the air permeability a loose relationship (fig. 9) was observed. Below an air permeability of $0.1 \cdot 10^{-16}$ m² (solid bold line) the maximum carbonation depth is less than 25 mm, the middle carbonation depth less than 15 mm and the minimum carbonation depth less than 6 mm. This loose relationship can be explained by the influence of the exposition: If concrete is always relatively dry or wet, even porous concrete experiences little carbonation; if the same concrete exhibits middle or changing moisture content, the carbonation process is much faster, resulting in higher carbonation depths. The data of Torrent & Frenzer [3] agree well with these results. Similar findings were observed for the chloride penetration. Generally, only a loose relationship exists, e.g. for low air permeability (less than $0.1 \cdot 10^{-16}$ m²) the chloride content in a concrete depth of 10 - 20 mm was less than 0.6 M.-% related to cement mass.

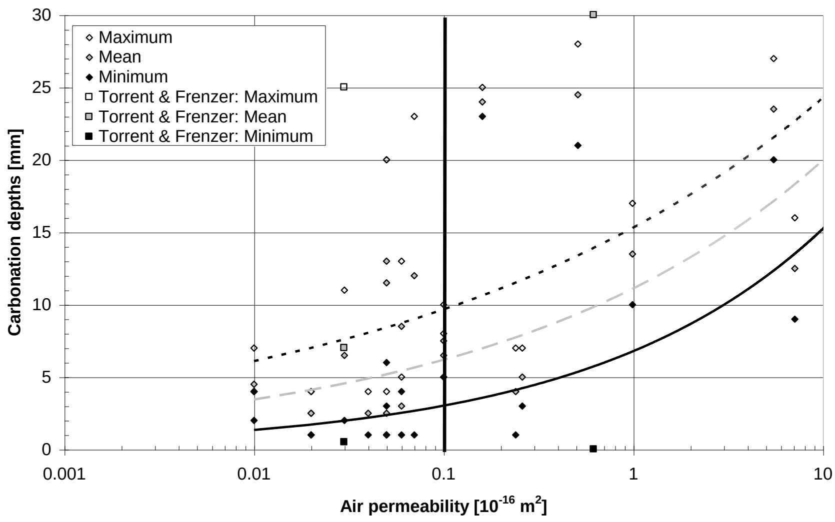


**Fig. 9: Carbonation depths as function of air permeability.**

## RECOMMENDED VALUES AND CONFORMITY CONTROL

Based on the findings the recommended limiting values for sufficiently dry, formed concrete surfaces are given in Table 1 as function of the exposure class acc. to SN EN 206-1. For non-formed concrete, e.g. trowelled surfaces, the available information is not sufficient to recommend limiting values.

**Tab. 1: Proposal for limiting values for maximum air permeability for formed concrete surfaces as function of the exposure class and the maximum w/c-ratio acc. to table NA.3 of SN EN 206-1. Additionally, mean values for a standard deviation $\sigma*$□ of 0.4 $m^2$ are given, which should be achieved, so that all measured values are below the maximum values with a probability of approximately 85 %.**

| Exposure class | max. w/c-ratio [-] | air permeability | |
|---|---|---|---|
| | | maximum value | geometric mean value for $\sigma$□* = 0.4 $m^2$ |
| | | $[10^{-16}\ m^2]$ | |
| XC1, XC2 | 0.65 | 1.00 | 0.40 |
| XC3 | 0.60 | 0.60 | 0.24 |
| XC4, XD1 - XD2, XF1 - XF3 | 0.50 | 0.40 | 0.16 |
| XD3, XF4 | 0.45 | 0.20 | 0.08 |

For the conformity control, i.e. to evaluate whether or not the values meet the requirements, the following criterion is proposed:

$$\log(kT_{geometric\ mean}) + \sigma* \leq \log(kT_{maximum\ value})$$

With this approach 85 % of all values lay with a probability of approximately 85 % below the recommended maximum value. If an air permeability of for example $0.4\cdot10^{-16}\ m^2$ is required and a standard deviation $\sigma*$□ of 0.4 $m^2$ is measured, the logarithm of the geometric mean has to be, according to the above equation, equal or lower than

$$\log(0.4\cdot10^{-16})\ m^2 - \sigma*□ = -16.40\ m^2 - 0.16\ m^2 = -16.58\ m^2$$

This value corresponds to an air permeability of $0.3 \cdot 10^{-16}$ $m^2$. In Tab. 1 maximum values for air permeability are given for various exposure classes. Additionally, geometric mean values, which are based on the above mentioned criterion, are given which have to be reached to comply with the recommended maximum values, if the standard deviation is 0.4 $m^2$.

## CONCLUSIONS

Based on the broad experiences with measuring the air permeability according to the Swiss standard SIA 262/1 the application of this method can be recommended as a non-destructive method to determine the impermeability (quality) of the cover concrete. Air permeability is an indicator for other durability properties like chloride migration coefficient, carbonation progress and capillary suction of water. Using this method the following restrictions have to be considered:

- Temperature: Air and concrete temperature should be > 5 °C.
- Moisture content of concrete: The specific electrical resistivity should be > 10 - 20 kΩcm or the moisture content, determined by capacity measurements, < 5.5 - 6.0 M-%.
- Age: At the time of measurement young concrete should have an age between approx. 1 - 2 months and approx. ca. 1.5 years.

## REFERENCES


[1] Matousek, cited in: Hansen, M. (2004): The effect of quality control on the reliability of structural concrete members (in German; Zur Auswirkung von Überwachungs-massnahmen auf die Zuverlässigkeit von Betonbauteilen).- Ph.-D. Thesis, Universität Hannover, 230 p.

[2] Torrent, R. & L. Ebensperger (1993): Study on methods to determine and evaluate characteristic parameters of cover concrete on-site (in German; Studie über Methoden zur Messung und Beurteilung der Kennwerte des Überdeckungsbetons auf der Baustelle).- VSS report, No. 506, 119 p, Zurich.

[3] Torrent, R. & G. Frenzer (1995): Study on methods to determine and evaluate characteristic parameters of cover concrete on-site (in German; Studie über Methoden zur Messung und Beurteilung der Kennwerte des Überdeckungsbetons auf der Baustelle).- VSS report, No. 516, Zurich.

[4] Romer, M. (2005): RILEM TC 189-NEC "Comparative test - Part I - Comparative test of penetrability methods.- Materials & Structures, 38, pp. 895 - 906.

[5] Jacobs, F. (2006): Air permeability as characteristic value for the quality of cover concrete of concrete structures (in German; Luftpermeabilität als Kenngrüsse für die Qualität des Überdeckungsbetons von Betonbauwerken).- VSS-Bericht, No. 604, 85 p., Zurich, can be downloaded at www.tfb.ch/publikationen.

[6] Romer, M. (2005): Effect of moisture and concrete composition on the Torrent permeability measurement.- Materials and Structures, 38, pp. 541 - 547.

[7] Kubens, St., E. Zellhuber, K. Rabald & R. Heidel (2005): Influence of curing on tightness and compressive strength of concrete (in German; Einfluss der Nachbehandlung auf die Dichtigkeit und Druckfestigkeit von Beton).- beton 1+2, pp. 20 - 22.

[8] CEB (1991): CEB-FIP Model Code 1990.- Comite euro-international du beton, Bulletin d'information 203, Lausanne.

[9] Jacobs, F. (1999): Durability properties of concrete (in German; Dauerhaftigkeits-eigenschaften von Betonen).- beton, pp. 276-282.

[10] Bakhshi, M., M. Mahoutian & M. Shekarchi (2006): The gas permeability and its relationship with strength.- fib, Proc. 2nd International Congress, Naples, Italy, Session 13, pp. 1 - 10.