NON DESTRUCTIVE TESTING OF THE CONCRETE COVER – EVALUATION OF PERMEABILITY TEST DATA

Frank Jacobs, Fritz Hunkeler

Technical Research and Consulting on Cement and Concrete, TFB, Wildegg, Switzerland

Abstract

The durability of reinforced concrete structures is determined to a great extent by the quality of the outer part of concrete, e.g. the concrete cover of the reinforcement. The European concrete standard EN 206-1 gives guidelines to produce durable concrete which are mainly based on provisions for the composition of concrete. It also contains some information for proper curing. In practice, e.g. curing is not always executed as planned. A procedure is, therefore, needed to check the quality of finished concrete elements. To evaluate the quality of the concrete cover a research project using non destructive air permeability measurements is carried out. Measurements were conducted in the laboratory as well as on concrete structures. Air permeability is influenced by concrete composition, moisture content and temperature of the concrete and the actual condition of the concrete cover, e.g. cracks, surface coatings. Advice will be given how concrete quality can be estimated based on air permeability measurements.

1 INTRODUCTION

Permeability measurements were developed and used since at least approximately 20 years to characterize the durability of concrete [1, 2, 3]. In the middle of the 1990ies the Torrent Permeability Tester (TPT) was developed [4, 5], in 2003 this method was introduced in the Swiss standard SIA 262/1 [6]. Prior to the TPT-measurement the atmospheric pressure in the inner chamber (

Figure 1) is reduced by a vacuum pump to approximately 10 - 20 mbar. During the measurement, air flows from the inner part of the concrete into the chamber. The pressure increase is recorded and air permeability is calculated according to Torrent [4, 5] by the equation (1) by an integrated control unit.

$$kT = \left(\frac{V_c}{A}\right)^2 \cdot \frac{\mu}{2\varepsilon p_a}\left[\frac{\ln\left(\frac{p_a + p_i}{p_a - p_i}\cdot\frac{p_a - p_o}{p_a + p_o}\right)}{\sqrt{t} - \sqrt{t_o}}\right]^2 \qquad (1)$$

kT: air permeability [m^2]
V_c: volume of inner chamber [m^3]
A: cross sectional area of inner chamber [m^2]
μ: viscosity of air [Ns/m^2]
ε: volume of air filled voids in concrete;
p_a: atmospheric pressure [N/m^2]
p_i: air pressure at time t (end of the measurement) in the inner chamber [N/m^2]
p_o: air pressure in the inner chamber at time t_o (start of measurement) [N/m^2]

fixed value: 0.15 [-]

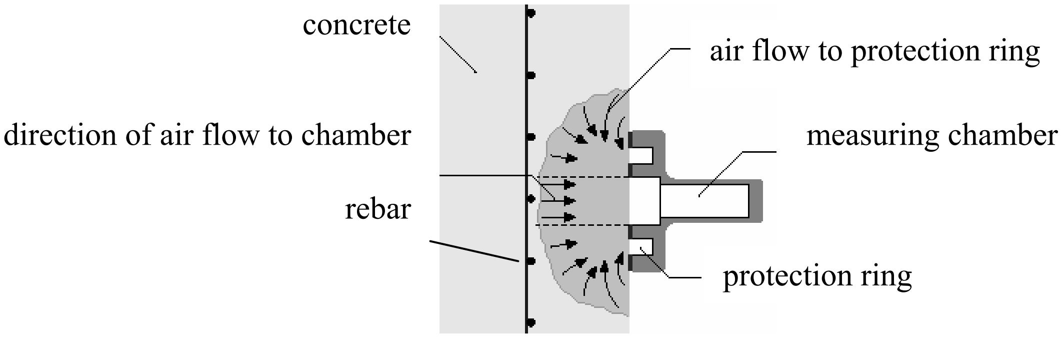

Figure 1: Sketch of the principle of TPT [6]

The moisture content of concrete has the strongest influence on air permeability [1, 2, 3]: a concrete of high porosity, but completely water saturated, has a lower air permeability than a dense but dry concrete. Hence it is essential to determine the water content of concrete for the interpretation of the air permeability results. Since some years several research projects have been started to study the applicability of TPT on-site. One of those projects [10] is financed by the Swiss Federal Roads Authority (ASTRA). From this project preliminary results will be presented. In the project investigations were carried out in the laboratory and on-site on new and old structures. The aims of this project are as follows:

- Determine the influence of concrete composition and environmental condition (humidity, temperature) on air permeability.
- Investigate the correlation between air permeability and concrete quality of new and old structures (e.g. carbonation depths, chloride content, strength).
- Prepare guidelines for the application of TPT on-site and the interpretation of the results.

2 EVALUATION OF THE RESULTS

Air permeability of concrete can vary over more than four orders of magnitude. Figure 2 shows results of air permeability measurements on structural members. Large variations of the air permeability of one single structural member can be observed. The large variations can be caused by differences in concrete quality and small cracks or surface irregularities. Jacobs [2] reported that cracks with a width of approximately 0.1 µm can lead to air permeability higher than 10^{-16} m^2, which are in general not relevant for the durability.

In order to characterize an element by one permeability value, the geometric mean was selected, which coincides with the arithmetic mean of the logarithm of the permeability data. The geometric mean gm of each element was calculated as following:

$$gm = (y_1 \cdot y_2 \cdots y_3)^{1/n} \qquad (2)$$

gm: geometric mean;
$y_1 \ldots y_n$: measured permeability values;
n: number of values;

The superiority of the geometric mean as representative value over to the arithmetic mean or the median is clearly shown in figure 3. The arithmetic mean is very strongly influenced by a few high air permeability values and therefore not appropriate. The median value is more useful than the arithmetic mean, but strongly influenced by the number of measurements; hence it is not further used.

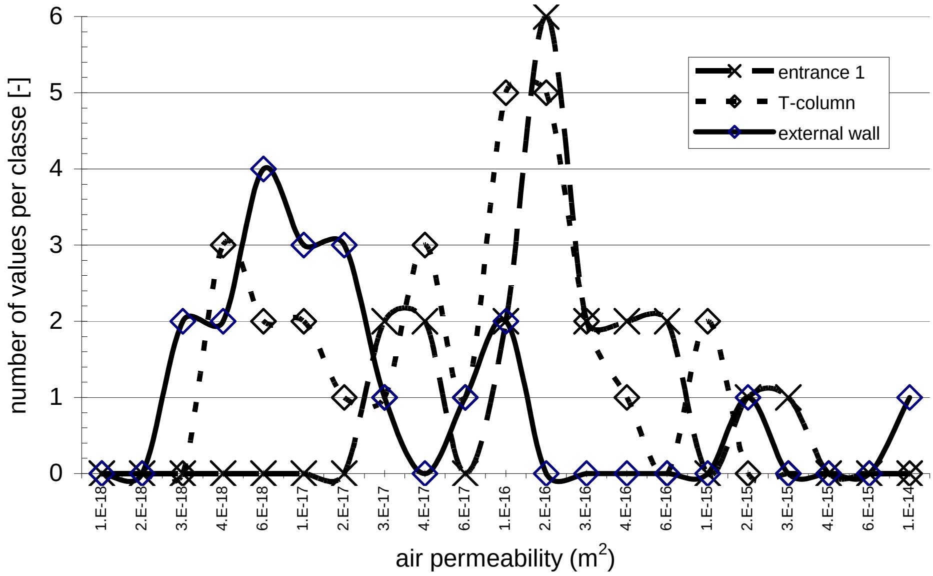

Figure 2: Results of air permeability measurements on different structural members

The geometric means were calculated with all and with selected permeability values. In a second step, high permeability values (extreme values), which indicate e.g. small cracks, surface irregularities were discarded. The border between "high" and "normal" values was selected as following: If two or more populations of permeability values (peaks in a plot like fig. 2) were visible, the values of the population with the lowest air permeability was regarded as representative for the concrete and used for further evaluations Regarding the large variations of all permeability data over orders of magnitude, only small variations exist when the selected permeability data are used (tab. 1).

	gm_a	gm_s	σ_a	σ_s
external wall	0.16	0.10	0.93	0.36
internal wall	2.36	1.42	0.68	0.37
T-column	0.34	0.24	0.71	0.63
entrance 1	1.53	1.19	0.51	0.41
entrance 2	0.66	0.53	0.49	0.34

Table 1: Geometric mean values gm and standard deviations σ calculated with all measurements (index a) and selected measurements (index s)

From the permeability data of each structural member, the standard deviation is calculated from the logarithm of the permeability data. These calculations have been chosen because the logarithm of the measured values shows a nearly normal distribution (fig. 2). In figure 4 standard deviation as function of air permeability is shown. In general, the geometric mean was less than 0.6. No correlation between air permeability and standard deviation can be seen. If extreme values are discarded (see above), the standard deviation decreases in general to less than 0.4 (fig. 5). This value represents the usual heterogeneity of uncracked concrete.

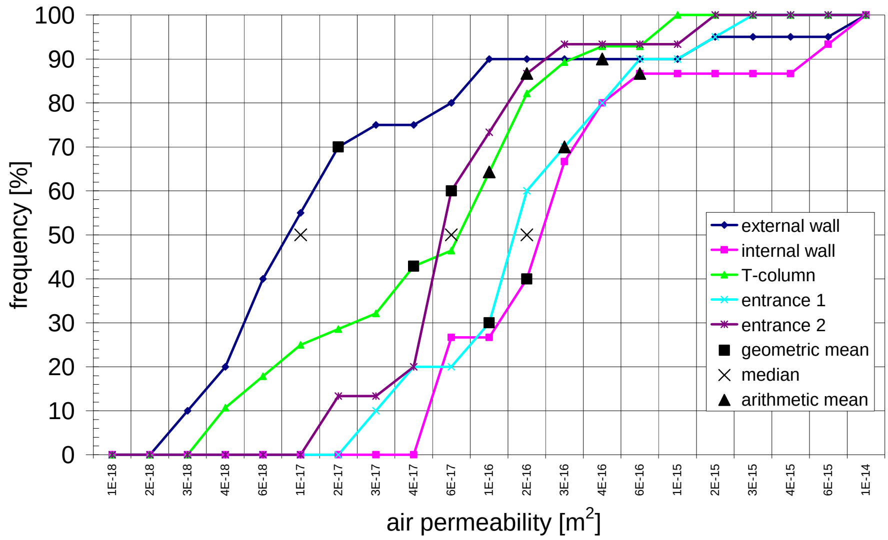

Figure 3: Distribution of air permeability values and various mean values for several structural members

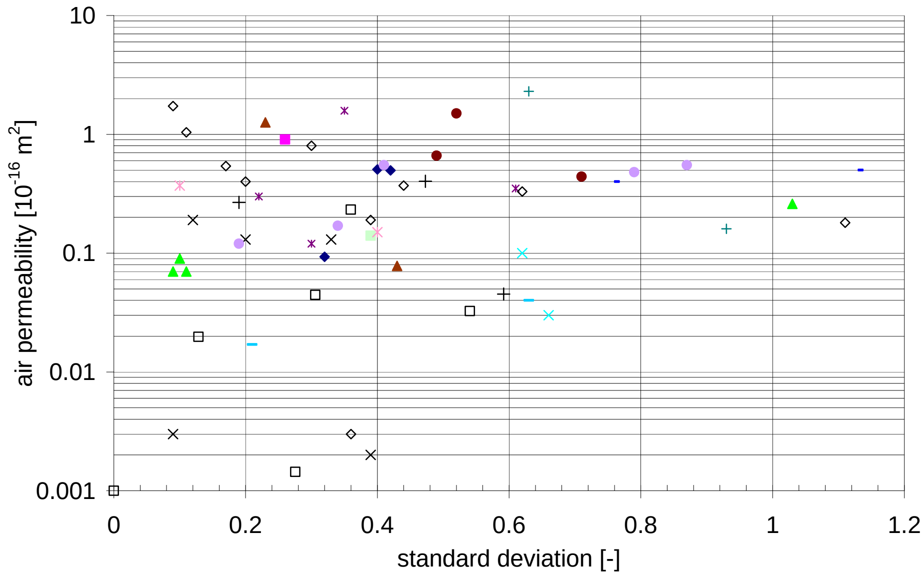

Figure 4: Standard deviation calculated from all measurements for each structural member as function of air permeability

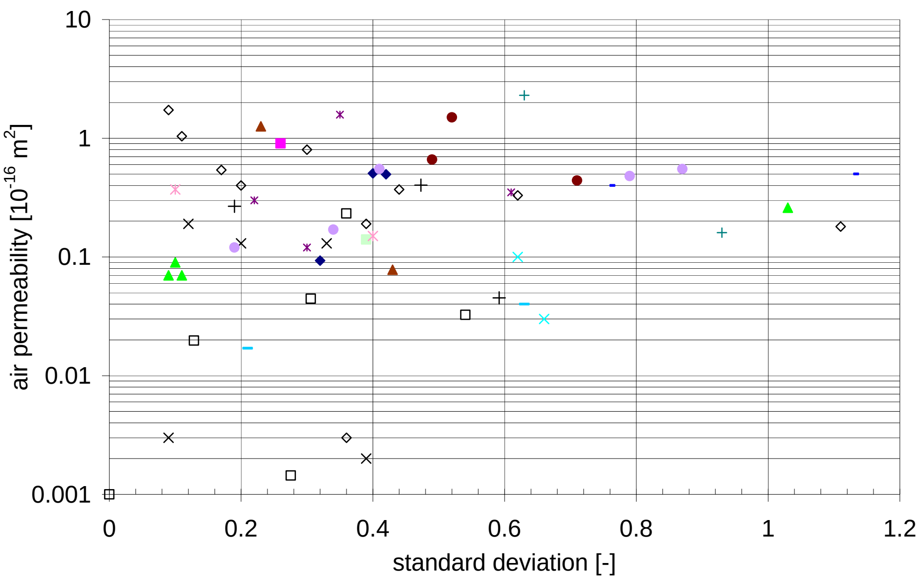

Figure 5: Standard deviation calculated from selected measurements from each structural member as function of air permeability for various construction elements

To evaluate concrete quality with air permeability values, it is necessary to link the obtained geometric mean of air permeability values to concrete composition. For this purpose the data from table 2 were used. Those were obtained from permeability measurements in the laboratory using the Cembureau method [1]. With this method the gas flow through concrete disks is monitored. It is known that the so called "gas slippage" contributes to the gas permeability, i.e. the gas permeability increases with decreasing pressure difference across the sample [2, 3]. This effect was accounted for in the laboratory measurements, but not for the air permeability measurements on site (method TPT). The age of the concrete for the laboratory measurements was between some months and less than 1.5 years. The concrete consisted mainly of cement CEM I according to SN EN 197-1. No reactive mineral additives were used.

Table 2: gas permeability of young concrete (< 1 ½ years), measured by Cembureau method in laboratory and w/c ratio of concrete [7]

classe	gas permeability k [10^{-16} m²]	Achievable with well cured concrete of w/c-ratio [-]
5	> 10	
4	< 10	0.80
3	< 1	0.60
2	< 0.5	0.50
1	< 0.1	0.40

One aim of the research project of TFB was to check whether the correlation between w/c-ratio and gas permeability of table 2 can also be used for air permeability measurements with TPT. In figure 6 results of air permeability measurements (geometric mean value) of structural members made of CEM I or CEM II/A-LL according to SN EN 197-1 with no reactive mineral additives and having an age of less than ½ year are plotted versus the w/c-ratio. The w/c-ratio was determined by testing the fresh concrete used for the manufacture of the elements. It can be seen that many points lay below the dotted line. If the correlation is valid for TPT measurements, too, a point lying above the dotted line means that air permeability is higher than those for a well cured concrete with the same w/c-ratio. An insufficient curing or surface irregularities can cause high permeability values. In general, the data of table 2 seems to be useful for a first, but gross evaluation of concrete quality, based on the w/c-ratio. Wet concrete (specific electrical resistivity < 15 kΩcm) and low air temperatures (< 5 °C) can give misleading (too low) results (fig. 6, [8]. This will be further investigated [10].

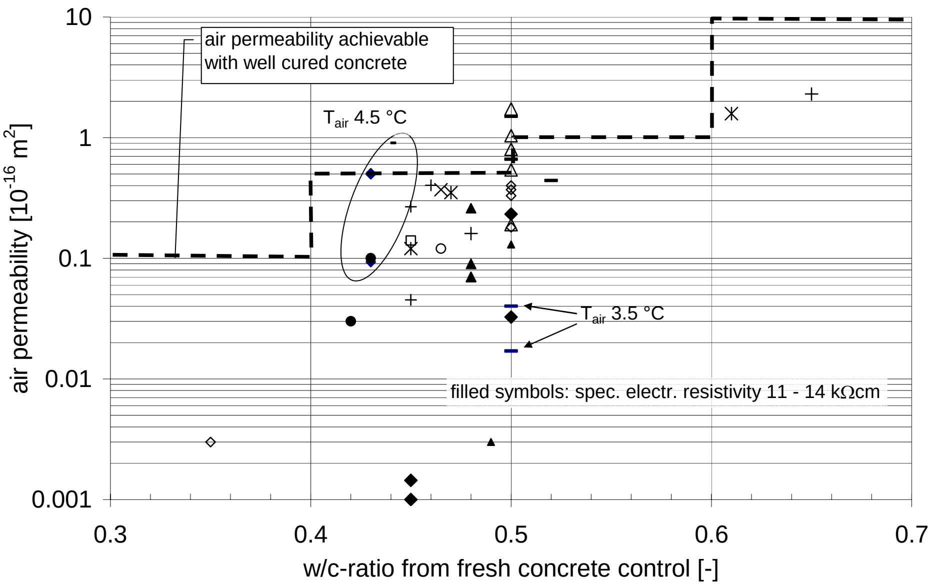

Figure 6: Results of air permeability measurements on site and w/c-ratios determined by fresh concrete tests

Figure 7 confirms the well known loose relationship between strength and air permeability of concrete. Compressive strength is influenced by the size and shape of the test specimen. In the results presented in figure 7 no corrections are made with respect to the geometrical influence, because it is small. Compressive strength gives only a rough estimation of concrete tightness and therefore on durability. In other words, a method (e.g. TPT) is needed to evaluate concrete durability based on tightness.

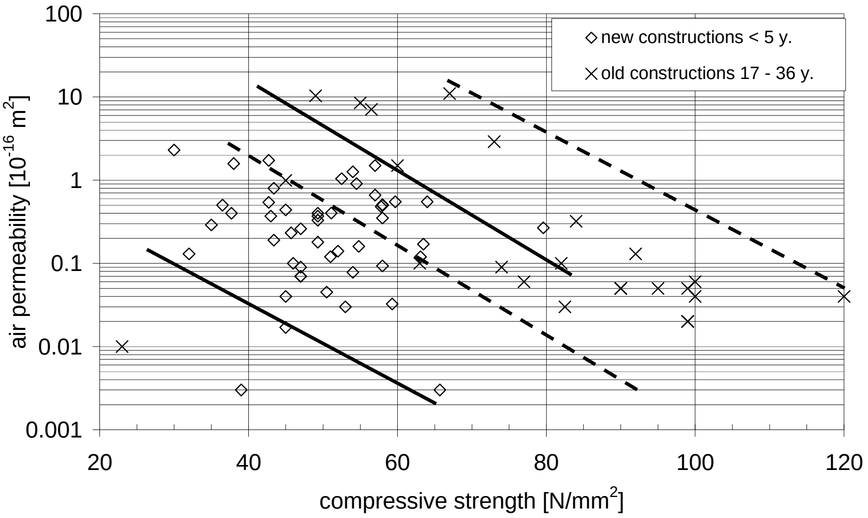

Figure 7: Results of air permeability measurements on site and compressive strength determined for new constructions on cubes having an age of 28 days and for old constructions on drilled cores (l = d = 50 mm).

3 RESULTS OF LABORATORY MEASUREMENTS

Concrete having w/c-ratios of 0.40, 0.50 and 0.60 and made of Portland cement CEM I according to SN EN 197-1 without and with reactive mineral additions (e.g. fly ash, silica fume) and Portland limestone cement CEM II/A-LL was investigated at an age of 28, 90 and 365 days. It was found, if air permeability exceeds $0.04 \cdot 10^{-16}$ m^2) only a minor influence of temperature between 5 and 30 °C results (fig. 8). At very low air permeability values (< $0.04 \cdot 10^{-16}$ m^2) a significant influence of temperature on air permeability was found: a temperature increase from 5 to 20 or 30 °C increased the air permeability by more than a factor of 6 (fig. 8).

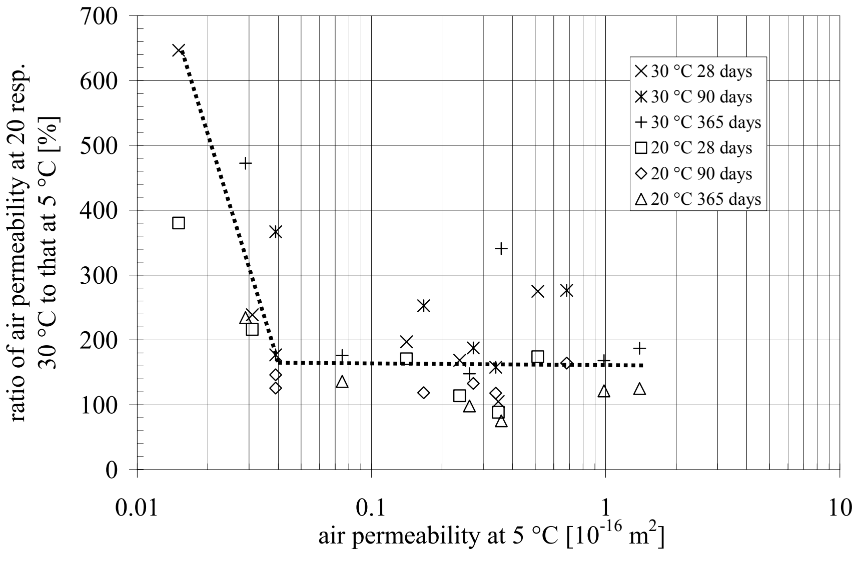

Figure 8: Influence of temperature and air permeability at 5 °C on air permeability measured at 20 and 30 °C.

It was proposed [4, 5] to determine the influence of moisture content by electrical resistivity measurements. The compilation of data in table 3 shows that concrete composition as well as moisture content strongly influences the specific electrical resistivity. Hence for a concrete of unknown composition it is probably not possible to estimate its water content solely on the basis of electrical resistivity measurements. From the measurements made so far, mainly on concrete without reactive mineral additions, specific electrical resistivity measurements might be used (fig. 6). This has to be investigated further.

Table 3: specific electrical resistivity of different types of concrete and storage condition [9]

environment	CEM I concrete	Concrete containing slag, fly ash, silica fume
	Specific electrical resistivity [kΩcm]	
Very wet, submerged, splash zone	5…20	30…100
Outside, exposed	10…40	50…200
Outside, sheltered, coated, hydrophobised, 80 % r.h., not carbonated	20…50	100…400
Ditto, carbonated	≥ 100	200…600 and higher
Indoor climate (50 % r.h.)	≥ 300	400…1000 and higher

4 CONCLUSIONS

There is an obvious need to determine the durability properties of concrete by non-destructive methods. The Torrent Permeability Tester (TPT) is investigated within the framework of a research project. Preliminary results indicate the usefulness of TPT, but some open questions, remain to be solved. Unsolved questions mainly concern the interpretation of air permeability values, because for instance the estimation of the moisture content of concrete and its influence on air permeability is not known accurately enough.

ACKNOWLEGDMENT
Financial support of Swiss Federal Roads Authority (ASTRA) is gratefully acknowledged.

REFERENCES

[1] Kropp, J. & H.K. Hilsdorf (ed). 1995: Performance criteria for concrete durability.- RILEM report 12, E & FN Spon, 327 pp
[2] Jacobs, F. 1994: Permeability and porous structure of cementitious materials (in German).- Building Materials Report No. 7, Aedificatio Publishers, IRB Verlag, 164 p.
[3] Jacobs, F. 1998: Permeability to gas of partially saturated concrete; Magazine of Concrete Research, 50, 2, 115 - 121
[4] Torrent, R. & L. Ebensperger 1993. Study on methods to determine and judge characteristic values of the cover concrete on site (in German).- Bundesamt für Strassenbau, Bern, No. 506, 117 p.
[5] Torrent, R. & G. Frenzer 1995. Study on methods to determine and judge characteristic values of the cover concrete on site (in German).- Bundesamt für Strassenbau, Bern, No. 516, 105 p.
[6] SIA 262/1: Concrete Structures– Supplementary Specifications (in German).- SIA Zürich, 40 p.
[7] Jacobs, F. 1999. Durability properties of concrete (in German).- beton, 5, pp. 276 - 282
[8] Romer, M. 1995. Effect of moisture and concrete composition on the Torrent permeability measurement.- Materials & Structures, 38, 541 - 547
[9] Polder, R. et al. 2000: Test methods for on site measurements of resistivity of concrete. RILEM TC 154-EMC, Materials & Structures, 33, 603-611
[10] Jacobs, F. 2006. Air permeability as characteristic parameter for the quality of cover concrete of concrete structures (in German).- Bundesamt für Strassenbau, Bern, to be published