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Specification and site control of the permeability of the cover concrete: The Swiss approach

Dedicated to Professor Dr. Bernhard Elsener on the occasion of his 60th birthday

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It is recognized that most damage to reinforced concrete structures is caused by insufficient durability rather than by low strength. In most cases, the quality and thickness of the cover concrete ("covercrete") determine the service life of the structure. Since the quality of the covercrete is influenced, not only by the mix composition, but also by the placing and curing conditions, it is appropriate to measure the achieved properties on the structure rather than just on separately cast specimens. Swiss Standard SIA 262 on "Concrete Construction" recommends checking the "impermeability" of the cover concrete on site. With that aim, a non-destructive method to measure the air-permeability on site has been standardized (SIA 262/1 Annex E). A team of Swiss experts was appointed by the Swiss Federal Highway Administration (ASTRA) to prepare recommendations for specifying, measuring, and assessing the conformity of the air-permeability *kT*. This paper describes these recommendations covering: (a) specification of limiting values of *kT* as function of the exposure class; (b) sampling of the measurement points; (c) testing (including suitable temperature and moisture conditions); (d) evaluation of conformity with specified values; (e) expected impact on service life.

1 Introduction

Since the early 1990s, ASTRA (Swiss Federal Highway Administration) has been supporting R&D projects oriented at developing a suitable approach for specifying and controlling the quality of the cover concrete on site [1–6]. This work, complemented by other investigations, led to the standardization in 2003 of a non-destructive test method, originally developed by *Torrent* [7], to measure the air-permeability of the cover concrete on site [8].

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In the same year, a new Swiss Code for Concrete Construction, SIA 262:2003, based on Eurocode 2, was issued [9]. This code describes the measures to be adopted in order to ensure durability and, acknowledging the importance of the ''impermeability'' of the cover concrete, specifically states:

(a) ''with regard to durability, the quality of the cover concrete is of particular importance''.
(b) ''the impermeability of the cover concrete shall be checked, by means of permeability tests (e.g., air permeability measurements), on the structure or on cores taken from the structure''.

However, no limiting values of the coefficient of air-permeability (kT) were specified nor conformity rules for compliance were given in the code.

To overcome this situation, ASTRA granted a project with the following aims:

(a) to specify limiting values of kT for typical exposure classes found in Switzerland.

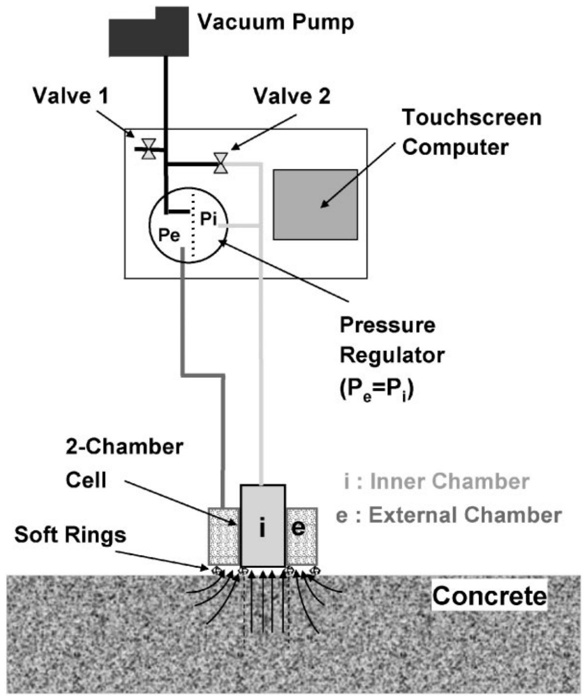

Figure 1. Sketch of air-permeability test

(b) to propose a concept for sampling measurement points within a structure.
(c) to provide guidelines for site measurement of air-permeability of concrete.
(d) to develop a compliance criterion to check conformity with the specified kT values.

A team of experts completed the task by the end of 2009 [6]; this paper summarizes the main aspects dealt with in the report.

2 Principles of test method SIA 262/1 Annex E

The method serves to measure the coefficient of air-permeability of the cover concrete on site, in a non-destructive manner and operates as follows.

Vacuum is created inside the two-chamber vacuum cell (Fig. 1), which is sealed onto the concrete surface by means of a pair of concentric soft rings, creating two separate chambers. At a time between 35 and 60 s (with a vacuum of ca. 5–50 mbar, depending on the concrete, instrument, etc.) valve 2 is closed and the pneumatic system of the inner chamber is isolated from the pump. The air in the pores of the material flows through the cover concrete into the inner chamber, raising its pressure P_i. The rate of pressure rise ΔP_i with time (measurement starts at $t_o = 60$ s) is directly linked to the coefficient of air-permeability of the cover concrete.

A pressure regulator maintains the pressure of the external chamber permanently balanced with that of the inner chamber ($P_e = P_i$). Thus, a controlled unidirectional flow into the inner chamber is ensured (Fig. 1) and the coefficient of permeability to air kT (m^2) can be calculated.

Figure 2 shows the main elements of the model. At time t, the vacuum front has reached a depth L; an instant dt later, the depth has grown dL, so as to contribute the volume of air dV that has entered the inner chamber in that time interval. The instrument registers an increase in pressure in the inner chamber of dP, due to the ingress of dV.

To calculate the coefficient of air-permeability kT, some assumptions are made for the air-flow into the vacuum cell:

(a) The concrete investigated by the test is homogeneous (in particular its porosity and permeability) and, at the beginning of the test ($t = 0$), all its accessible porosity contains air at the atmospheric pressure P_a.

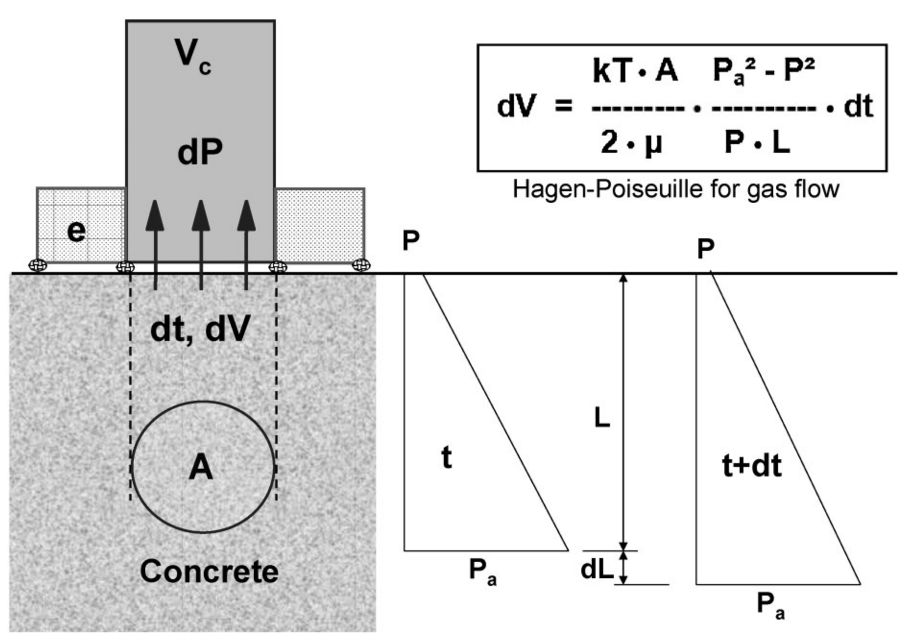

Figure 2. Basics of the model to calculate kT

(b) The thickness of the tested element is larger than the calculated penetration depth of the test L [calculated after Equation (2)].
(c) The distribution of pressure along the air path of the test Y is linear (strictly valid for steady-state conditions and laminar flow).
(d) The external chamber "e" is always at the same pressure as the inner measurement chamber, and the flow of air into the latter is laminar and perpendicular to the concrete surface along the whole duration of the test.
(e) At all times the pressure P in the inner chamber (10–60 mbar) remains negligible compared to P_a.

Applying the Hagen–Poiseuille law for compressible fluids, under the assumptions of the model, the coefficient of air-permeability is calculated with Equation (1); a full derivation can be found in Ref. [10].

$$kT = \left(\frac{V_c}{A}\right)^2 \frac{\mu}{2\varepsilon P_a} \left(\frac{\ln \frac{P_a + \Delta P_i}{P_a - \Delta P_i}}{\sqrt{t_f} - \sqrt{t_o}} \right)^2 \quad (1)$$

where kT is the coefficient of air-permeability (m^2); V_c the volume of inner cell system (m^3); A the cross-sectional area of inner cell (m^2); μ the viscosity of air at 20 °C ($= 2.0 \times 10^{-5}$ Ns/m^2); ε the estimated porosity of the cover concrete (default value assumed = 0.15); P_a the atmospheric pressure (N/m^2); $\triangle P_i$ the pressure rise in the inner cell at the end of the test (N/m^2); t_f the time (s) at the end of the test (120–360 or 720 s, depending on the instrument brand); and t_o is the time (s) at the beginning of the test (= 60 s).

The maximum penetration depth L (mm) of the vacuum front can be calculated with Equation (2). L is larger for concretes with higher kT, varying typically between 10 and 70 mm.

$$L = 1000 \left(\frac{2 \cdot kT \cdot P_a \cdot t_f}{\varepsilon \cdot \mu} \right)^{1/2} \quad (2)$$

3 Specified limiting *kT* values

The specified values of the coefficient of air-permeability (kT_s) after [6], as function of the exposure classes of the Swiss version of Standard EN 206-1 [9], are shown in Table 1.

As discussed later, the kT_s values are maximum "characteristic" values.

4 Sampling of test areas and measurement points

4.1 Grouping

The structure to be evaluated should be divided into groups of elements that have the following features in common:

(a) same specified air-permeability value kT_s (see Table 1).

Table 1. Limiting values of kT specified as function of the exposure conditions

Exposure	EN 206 classes	kT_s (10^{-16} m^2)
Moderate carbonation	XC1, XC2, XC3	Not required
Severe carbonation	XC4	2.0
Moderate chlorides	XD1, XD2a	
Moderate frost	XF1, XF2	
Severe chlorides	XD2b, XD3	0.5
Severe frost	XF3, XF4	

(b) were built with concrete belonging to the same EN 206-1 class (same strength, aggregate size, and exposure class).
(c) were built applying similar concreting practices (placing, compaction, curing, etc.).

For compliance purposes, all the elements in the structure presenting the same features (a)–(c), described above, will constitute a group. They should be listed chronologically, within each group, by date of concreting; in the case of continuous elements (e.g., walls or deck slabs), segments concreted on the same day should be identified.

4.2 Test areas

The elements within each group will be divided into test areas (lots) according to the following criterion (the resulting maximum number of test areas should be adopted):

(a) one test area per each 500 m^2 of exposed surface area or extra fraction thereof.
(b) one test area per 3 days of concreting of the elements of the group.

4.3 Measurement points

From each resulting test area, six measurement points will be sampled at random, avoiding excessive closeness to edges (especially top and bottom) and to each other.

5 Age, temperature, and moisture conditions of the concrete

5.1 Age of concrete

The age of concrete when tested should be between 28 and 90 days. In particular, when slow-reacting cements (e.g., CEM III/B) or significant amount of slow-reacting mineral additions such as fly-ash are used, a minimum age of concrete of 60 days should be considered.

Considerable efforts were devoted to establish, based on existing information [1, 2, 11, 12], the appropriate conditions under which the test method provides meaningful results. Provisions were taken to avoid that the concrete, at the moment of test, is too cold and/or with too high degree of saturation. The latter, in particular, is known to have a strong influence of the measured values. A full section of the report [6], gives justification to those provisions, summarized below.

5.2 Temperature of concrete

The surface temperature of the construction element, measured for instance with an infrared thermometer, should be above 10 °C. Experienced users can, if necessary, measure at temperatures between 5 and 10 °C. Depending on the type of device used, temperature has been found to influence more or less calibration values. This effect seems to be due to the sensitivity of some components to low temperatures and is being investigated in order to overcome it. Outdoor pilot tests at temperatures between 0 and 5 °C, conducted within the frame of RILEM TC 230-PSC, indicate that the problem is solvable in order to further extend the range of applicability of the method.

5.3 Moisture conditions of concrete

(a) The moisture content should not exceed 5.5% (by mass) when determined with the concrete moisture encounter instrument (manufactured by Tramex, based on measuring the electrical impedance) or
(b) The electrical resistivity, measured by the Wenner probe (manufactured by Proceq) shall not be below 10 or 20 kΩ/cm at 20 °C. The lower value applies to concretes made with CEM I (OPC) and the upper for binders containing reactive mineral additions such as fly-ash. In case the temperature is below 15 °C or above 25 °C, a conversion of the electrical resistivity to 20 °C should be made. If data of the variation of the electrical resistivity with temperature are not available for the investigated concrete, the rule that between 5 and 40 °C the electrical resistivity is halved for a temperature increase of 20 °C can be applied [3].

The achievement of the above conditions depends strongly on the ambient conditions and will generally be reached when:

(a) the curing ended 3–4 weeks prior to the test.
(b) more than 2–5 days have passed after the last ingress of water in the concrete by, for instance, rain, spray, or thaw.

If the right test conditions cannot naturally be met, the test areas should be protected from wetting and allowed to dry until at least one of the conditions is fulfilled.

6 Conformity rules and reporting

6.1 Conformity rules

Each test area must satisfy the following conditions:

Condition 1: Out of the six air-permeability values kT_i, measured on a test area, as described in Section 4.3, not more than one can exceed the specified air-permeability limit value kT_s.

In case that just two out of the six air-permeability values kT_i, measured on a test area, exceed the specified air-permeability limit value kT_s, another six further air-permeability tests can be conducted on six new measurement points selected from the same test area.

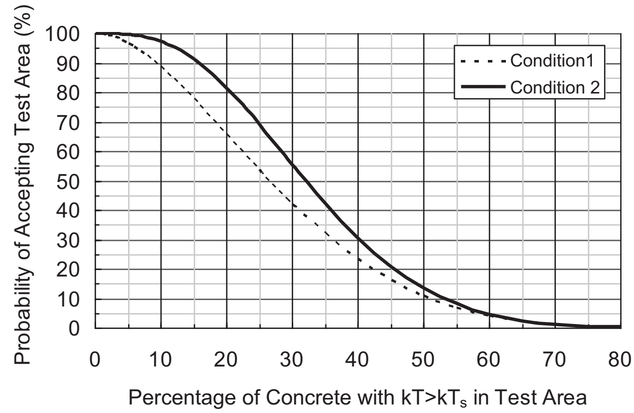

Figure 3. O–C curve of the compliance criterion

Condition 2: Not more than one air-permeability value kT_i out of the six new determinations can exceed the specified air-permeability limit value kT_s.

If neither Condition 1 nor Condition 2 is satisfied, the test area is considered as not in conformity with the specifications and complementary/remedial measures have to be taken.

As the O–C curve of the compliance criterion shows (Fig. 3), a test area composed by just 10% of non-compliant concrete (i.e., with $kT > kT_s$) has about 90% of probability of being accepted with Condition 1 and more than 95% of being accepted with Condition 2. On the other hand a test area composed by 25–30% of non-compliant concrete has only about 50% of probability of being accepted. This gives a clearer statistical meaning of kT_s as "characteristic" air-permeability upper limit.

A report form is proposed to present results and relevant information as well as special circumstances that may have been encountered during the measurements (e.g., cracks, surface protective treatments, coatings).

7 Why air-permeability as durability indicator?

Several researches have shown that the coefficient of air-permeability kT correlates quite well with other standardized durability-related tests [6]. For instance, Figs. 4 and 5 show data of water sorptivity (SIA 262/1 Annex A) and carbonation depth (RILEM Recommendation CPC 18) of concretes after 500 days of natural exposure (20 °C, 50% RH), respectively, and their kT values measured at 28 days, data from Refs. [1, 2]. The investigations covered concretes with w/c in the range 0.26–0.75, made with OPC (except few mixes to which 5–8% silica fume was added) and cured 0 and 7 days in the moist room before being placed at 20 °C and 50% RH storage.

Figure 6 presents the correlation of kT with the mean penetration of water under pressure (EN 12390-8 and DIN 1048), data from Refs. [13–19]. The data taken from [13] correspond to cores drilled from the top and lateral surfaces of panels made with OPC mixes with w/c ratios of 0.41 and 0.59. Different finishing

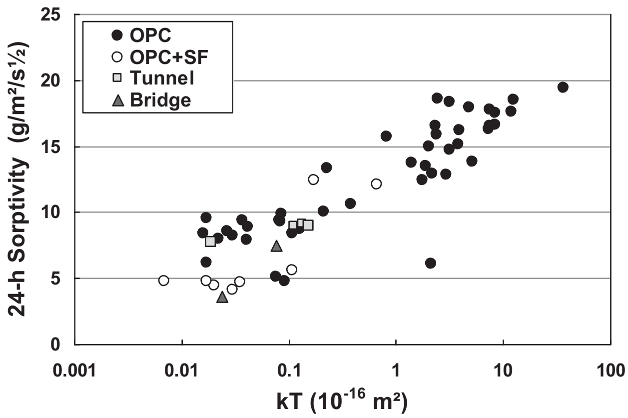

Figure 4. Relation between water sorptivity and air-permeability *kT*

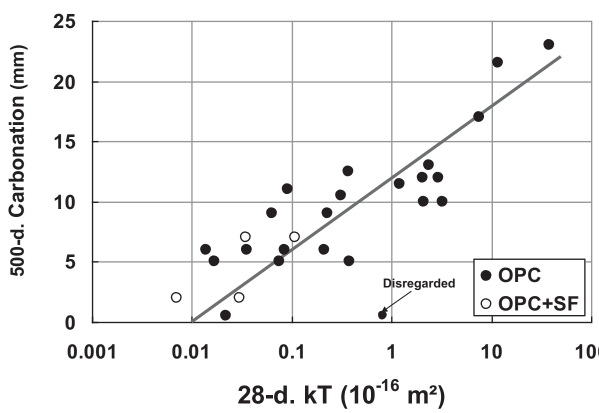

Figure 5. Relation between natural carbonation and air-permeability *kT*

techniques of the top surface and a ''Zemdrain'' permeable form liner were applied. After *kT* measurement directly on the panels, tests were performed according to DIN and EN procedures on drilled cores. The data from Ref. [14] correspond to pozzolanic cement concretes with *w*/*c* 0.40 and 0.45 intended for a LNG tank in México. The data from Ref. [15] correspond to SCC (self-compacting concrete) panels made with *w*/*c* ratios 0.44 and 0.47 and a conventional concrete of *w*/*c* = 0.40. The data from Ref. [16] correspond to SCC mixes with *w*/*c* ratio 0.54, made with OPC and a blend of OPC and electro-filter powder from a cement plant. The data from Ref. [17] corresponds to a tunnel mix used for the Buenos Aires metro. The data from Ref. [18] correspond to a conventional concrete made with a triple-blend cement (containing slag and silica fume) and to four mixes where different vinyl-based polymers were added (*w*/*c* ratio ranging between 0.33 and 0.48). Finally, the data from Ref. [19] correspond to panels made with mixes containing OPC-CEM I cement and slag cement-CEM III/B, at *w*/*c* of 0.40 and 0.57, subjected to 1 and 7 days of moist curing.

Finally, Fig. 7 presents the correlation between *kT* and charge passed (Coulombs) in the ''Rapid Chloride Permeability Test'' ASTM C1202, data from Refs. [11, 15, 20–25]. The data from Ref. [11] correspond to panels made with OPC and slag cement mixes of *w*/*c* ratio in the range 0.40–0.60 subjected to different curing and storage conditions. Data from Ref. [20] correspond to mixes made with OPC, slag, fly-ash and silica fume binders, with *w*/*c* ratios 0.40 and 0.70, cured in plastic bags for 3 and 7 days. The data taken from Ref. [21] correspond to OPC mixes with high *w*/*c* ratios (0.55 and 0.88) subjected to different curing conditions, hence the high values reported. The data taken from Ref. [23] correspond to high volume of fly ash mixes, made with OPC and the addition of up to 40% of fly-ash (on the total binder), with w/(c + f) ratios between 0.52 and 0.65. The data from Ref. [24] correspond to cores drilled from 15 concrete pavements, mostly at least 20 years old, located in different climatic zones of USA. The core compressive strength ranged between 32 and 75 MPa. The values of *kT* were measured at the center of a cut Ø150 mm core, whilst the current passed corresponds to the average of tests conducted on 3 to 4 slices (50 mm thick) of Ø100 mm cores. The data from Ref. [25] correspond to concretes made with OPC and *w*/*c* ratios in the range 0.21–0.33; some of the mixes contained pumice coarse sand to provide a ''self-curing'' effect. The specimens were seal-cured at 30 °C and then exposed to natural drying; the specimens

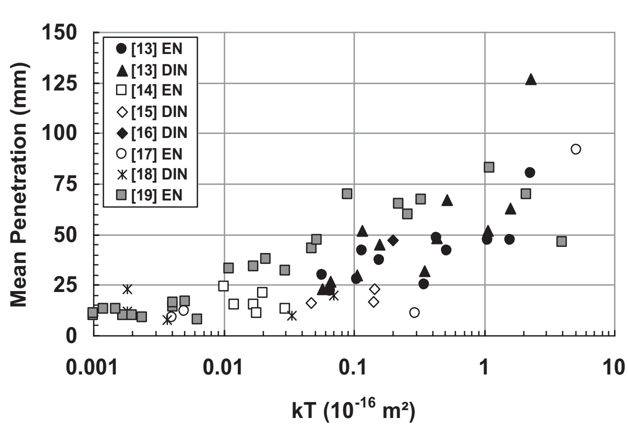

Figure 6. Relation between mean water penetration under pressure and *kT*

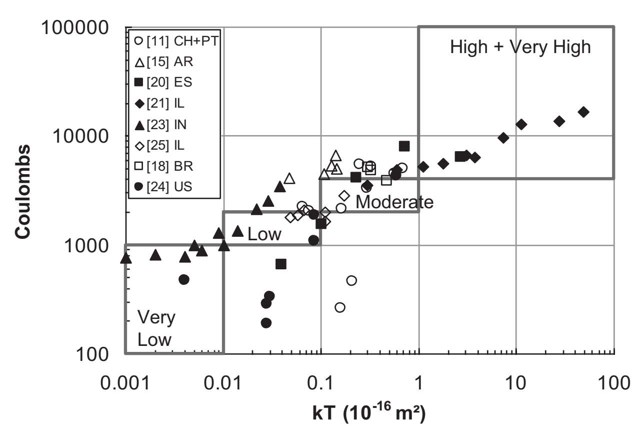

Figure 7. Relation between electric charge passed (ASTM 1202) and *kT* (permeability classes of both methods indicated)

for kT test were oven dried at 60 °C for 7–8 days till constant mass prior to testing.

Considering the variety of sources and concrete types involved in Figs. 6 and 7, the general trend confirms that the higher the kT value the higher the water penetration and the charge passed of the concretes. In Fig. 7, the rating given by both ASTM C1202 and kT methods are shown, indicating a reasonable agreement. A perfect correlation between these two tests can never be expected, since kT depends on the pore structure of the concrete whilst the charge passed is also strongly influenced by the ion composition of the electrolyte (the pore solution). This can be observed in the two white dots of series [11], corresponding to slag cement concretes, showing much lower charge passed, for the same kT, than the companion OPC mixes.

Within the framework of the ASTRA project, two comparative inter-laboratory tests were performed (on a bridge and a tunnel, respectively) to test the reproducibility of the kT measurements, in which five Swiss laboratories participated. The involved laboratories conducted, on site, between 6 and 15 measurements of kT on predefined test areas. Figure 8 shows the results obtained in the bridge, where kT_{gm} is the geometric mean of the readings and SD log kT the standard deviation of their decimal logarithms. The results show a very good reproducibility of the test method.

In the tunnel, two different commercial instruments were involved (''Torrent permeability tester'' and ''PermeaTORR''). A part of the experiment consisted in applying both instruments exactly on the same spots, with a delay of at least 1.5 h between successive measurements. The results showed a systematic difference between both instruments, especially for low kT values ($<0.1 \times 10^{-16}\,m^2$), confirming the trend found by other researchers (Fig. 9).

Romer [12] attributed the high kT values for low-permeability and rather moist concrete (>5.5% by mass), yielded by the manually-operated ''Torrent permeability tester'', to an initial high pressure increase due to moisture vaporizing into the inner chamber at very deep vacuum. To avoid this effect, the computer-controlled ''PermeaTORR'' has been designed to work above the water vapor pressure (30 mbar as default, definable by the user), minimizing that effect [26].

Figure 9 shows that, within the range of compliance with the specified kT values (0.5 and $2.0 \times 10^{-16}\,m^2$), both instruments

Test Area	Lab	kT_{gm} ($10^{-16}\,m^2$)	SD log kT
1	1	0.25	0.58
	2	0.13	0.68
	3	0.12	0.32
	4	0.22	0.42
	5	0.17	0.61
2	1	0.16	0.45
	2	0.10	0.32
	3	0.19	0.32
	4	0.20	0.30
	5	0.17	0.33

Figure 8. Comparative inter-laboratory test: results obtained on a bridge

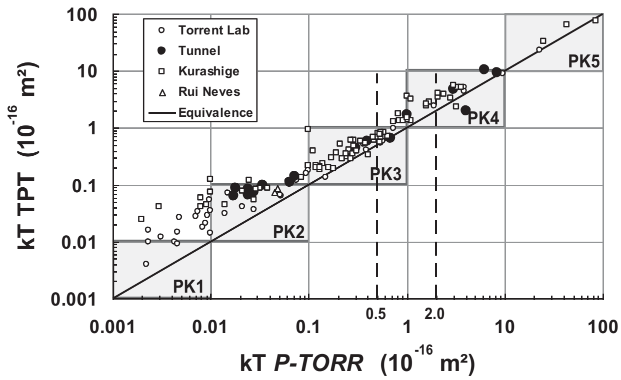

Figure 9. "In situ" kT results obtained in the tunnel (•) with the "Torrent permeability tester" (TPT) and the "PermeaTORR" (P-TORR), compared with results of other researchers

yield similar results and, thus, can be used indistinctly for compliance control.

The results of air permeability tests fall in general in line with results of other durability tests. As mentioned already, it cannot be expected that a perfect correlation for all types of concrete and environments be obtained. The non-destructive measurement of air permeability on-site allows to control the end-quality of the construction, including workmanship on-site.

8 Conclusions

The ASTRA Recommendations [6] set the stage for the specification and control of the air-permeability on site. This will certainly have a positive effect on the quality and durability of concrete structures in Switzerland, with the following expected benefits:

(a) By controlling the finished product, a performance-oriented mindset is consolidated in all the parties involved in the construction process (specifiers, contractors, material suppliers, inspectors, etc.).
(b) All too common bad practices (uncontrolled water addition to concrete trucks, poor compaction, lack of curing, improper slabs finishing, etc.) will be eradicated.
(c) The use of innovative solutions to improve the quality of cover concrete (permeable membranes for formworks, vacuum ''dewatering'' of slabs and the use of special concretes, such as self-compacting, high performance, or self-curing, etc.) will be encouraged.

It is expected that these recommendations will become part of the Swiss Standards in 2013 (draft under discussion).

As more experience is accumulated, the specified limiting values of kT as well as the boundary conditions for performing the tests (age, temperature, moisture) can be refined.

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