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

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It is recognised 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. Further, due to the increasing use of slow reacting cementitious materials like slag and fly ash, proper curing will become much more important in the future.

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 (SIA 2006b) on "Concrete Construction" recommends checking the "impermeability" of the cover concrete on site. A non-destructive method to measure the Air-Permeability on Site has been standardized (SIA 262/1 Annex E), allowing the assessment of the resistance of the concrete to the penetration of deleterious agents.

Based on the experience accumulated on over 100 construction elements examined, a team of Swiss experts was appointed by the Swiss Federal Dept. of Transportation (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) and d) evaluation of conformity with specified values.

The growing requirements for site concrete air-permeability determination will lead to improvements in the construction process, such as eradication of the bad habit of adding water to the trucks and more care put into placement and curing and even to the application of other techniques that improve the tightness of the cover concrete (e.g. permeable formwork liners, vacuum dewatering, UHPC layers, etc.) which will result in an extended service life of the constructions.

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ABSTRACT: It is recognised 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. Further, due to the increasing use of slow reacting cementitious materials like slag and fly ash, proper curing will become much more important in the future.

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1 INTRODUCTION

Since the early 90's, ASTRA (Swiss Federal Bureau of Roads) has been supporting R&D projects oriented at developing a suitable approach for specifying and controlling the quality of the cover concrete on site, Torrent and Ebensperger (1993), Torrent and Frenzer (1995), Brühwiler et al (2005), Denarié et al (2005), Jacobs (2006), Jacobs et al (2009). This work, complemented by other investigations, led to the standardization in 2003 of a non-destructive test method, originally developed by Torrent (1992), to measure the air-permeability of the cover concrete on site, SIA (2003).

In the same year, a new Swiss Code for Concrete Construction, SIA 262:2003, based on Eurocode 2, was issued, SIA (2003b). 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
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, Jacobs et al (2009); 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.

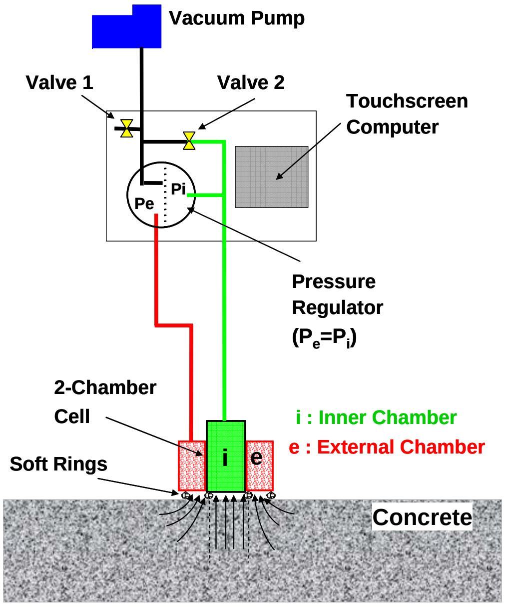


Fig. 1 – Sketch of test.

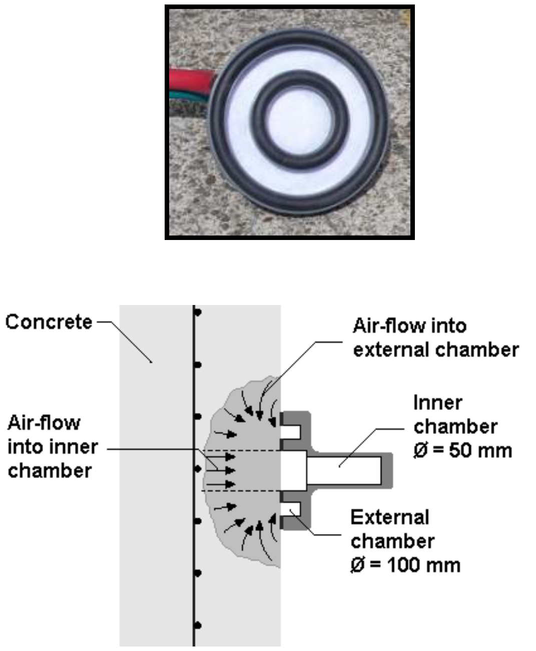


Fig. 2 –Vacuum cell and air-flow into both chambers.

Vacuum is created inside the 2-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 sec (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. 2) and the coefficient of permeability to air kT (m^2) can be calculated for a semi-infinite body; derivation available in Torrent (2009), with correction for finite bodies.

3 SPECIFIED LIMITING kT VALUES

The specified values of the coefficient of air-permeability (kT_s), as function of the exposure classes of the Swiss version of Standard EN 206-1, are shown in 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 Moderate Chlorides Moderate Frost	XC4 XD1, XD2a XF1, XF2	2.0
Severe Chlorides Severe Frost	XD2b, XD3 XF3, XF4	0.5

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:

1) same specified Air-Permeability value kT_s (see Table 1)

2) were built with concrete belonging to the same EN 206-1 class (same strength, aggregate size and exposure class)

3) were built applying similar concreting practices (placing, compaction, curing, etc.)

For compliance purposes, all the elements in the structure presenting the same features 1) to 3), 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):

- 1 Test Area per each 500 m^2 of exposed surface area or extra fraction thereof
- 1 Test Area per three days of concreting of the elements of the Group

4.3 Measurement Points

From each resulting Test Area, 6 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

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, Torrent and Ebensperger (1993), Torrent and Frenzer (1995), Romer (2005 and 2005a), 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 (B-2) of the Report, Jacobs et al (2009), gives justification to those provisions.

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.

Moisture Conditions of Concrete:

- 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
- 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 without reactive mineral additions such as fly-ash. In case the temperature is < 15°C or > 25°C, a conversion of the electrical resistivity to 20°C should be made (guidelines given)

6 CONFORMITY RULES AND REPORTING

6.1 Conformity Rules

Each Test Area must satisfy the following conditions:

Condition 1: Out of the 6 air-permeability values kT_i, measured on a Test Area, as described in Section 4.3, not more than 1 can exceed the specified Air-permeability limit value kT_s.

In case that just 2 out of the 6 air-permeability values kT_i, measured on a Test Area, exceed the specified air-permeability limit value kT_s, another 6 further Air-permeability tests can be conducted on 6 new Measurement Points selected from the same Test Area.

Condition 2: Not more than 1 air-permeability value kT_i out of the 6 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 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 presented during the measurements (e.g. cracks, SPT, coatings).

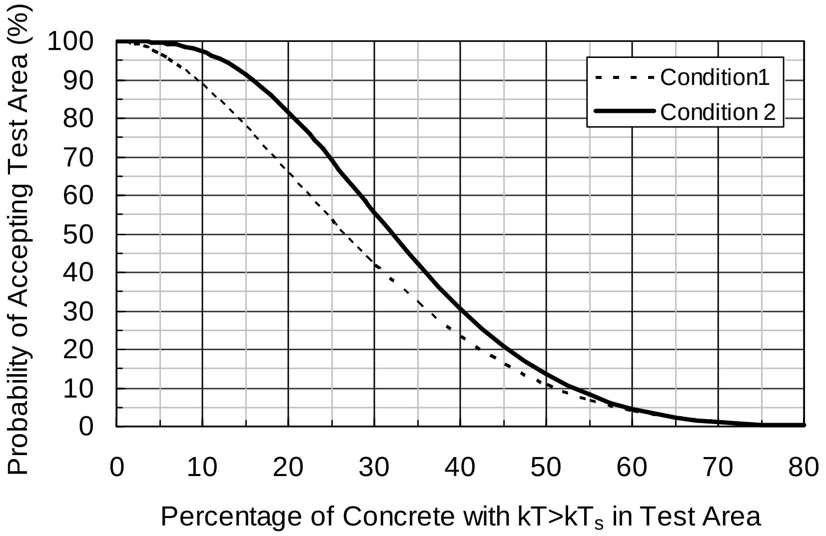


Fig. 3. O-C Curve of the Compliance Criterion

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, Jacobs et al (2009). For instance, Figs. 4 and 5 show data of water sorptivity (SIA 262/1Annex 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 Torrent and Ebensperger (1993) and Torrent and Frenzer (1995). Fig. 6 presents the correlation of kT with the mean penetration of water under pressure (EN 12390-8 and DIN 1048), data from Denarié et al (2004), Fernández Luco et al (2005), Fornasier et al (2003), Di Pace et al (2008), Rodríguez et al (2005), Kattar et al (1995) and van Eijk (2009). Finally, Fig. 7 presents the correlation between kT and Coulombs passed in the 'Rapid Chloride Permeability Test' ASTM C1202, data from Romer (2005), Andrade et al. (2005), Kubens et al (2003), Mathur et al (2005), Kattar et al (1995, 1999), FHWA (2000), Fornasier et al. (2003). Interesting to remark is the variety of countries contributing to the results in Figs. 6 and 7 (ISO country codes indicated).

To test the reproducibility of the kT measurements, two comparative inter-laboratory tests were performed within the frame of the ASTRA Project, in which five Swiss laboratories were involved. The involved laboratories conducted, on site, between 6 and 15 measurements of kT on predefined Test Areas. Fig. 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 hours between successive measurements. It was confirmed that, within the range of compliance with the specified values (0.5 and 2.0 10^{-16} m ^{2}), both instruments yield similar results (Fig. 9) and, thus, can be used indistinctly for compliance control.

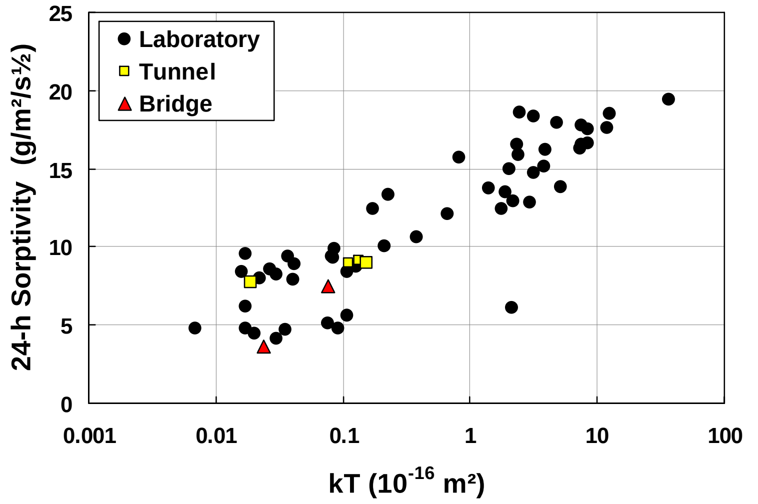


Fig. 4. Relation between water sorptivity and air-permeability kT

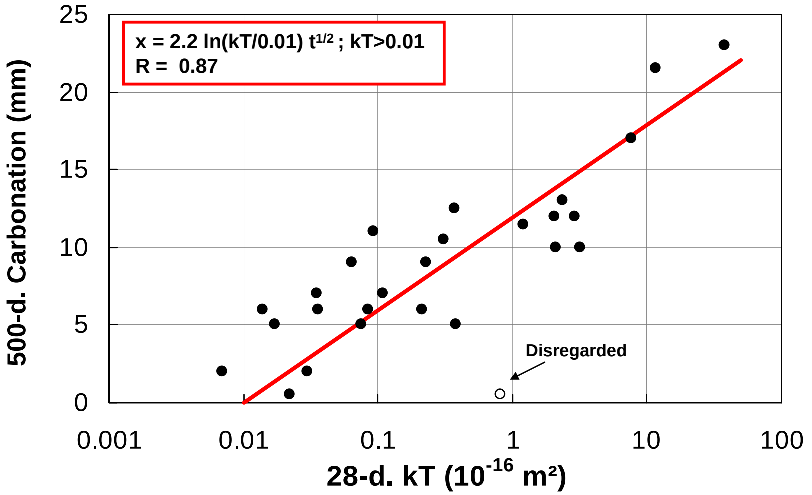


Fig. 5. Relation between natural carbonation and air-permeability kT

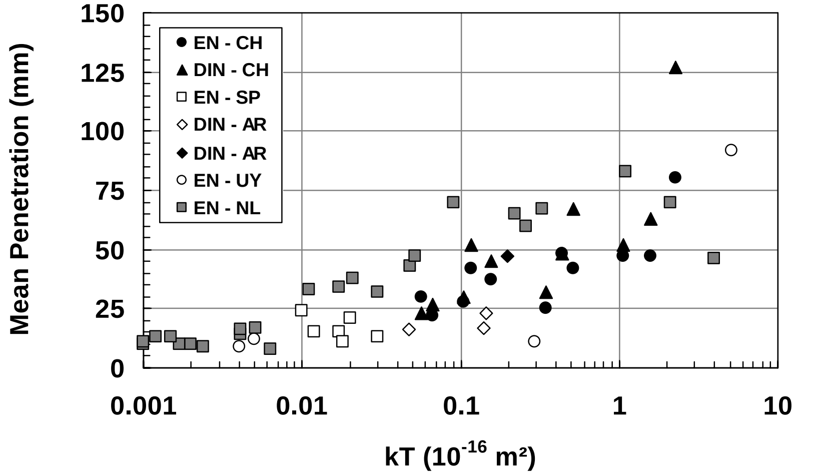


Fig. 6. Relation between water penetration under pressure and air-permeability kT

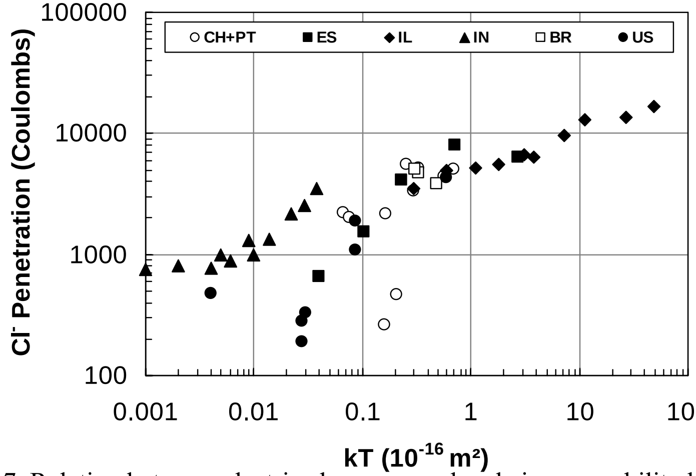
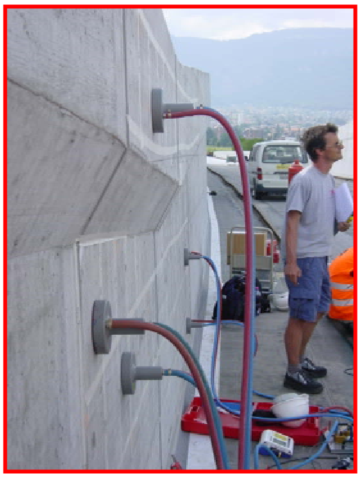


Fig. 7. Relation between electric charge passed and air-permeability kT



Test Area	Lab	kT_{gm} (10^{-16} m²)	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

Fig. 8. Comparative inter-laboratory test: results obtained in a bridge

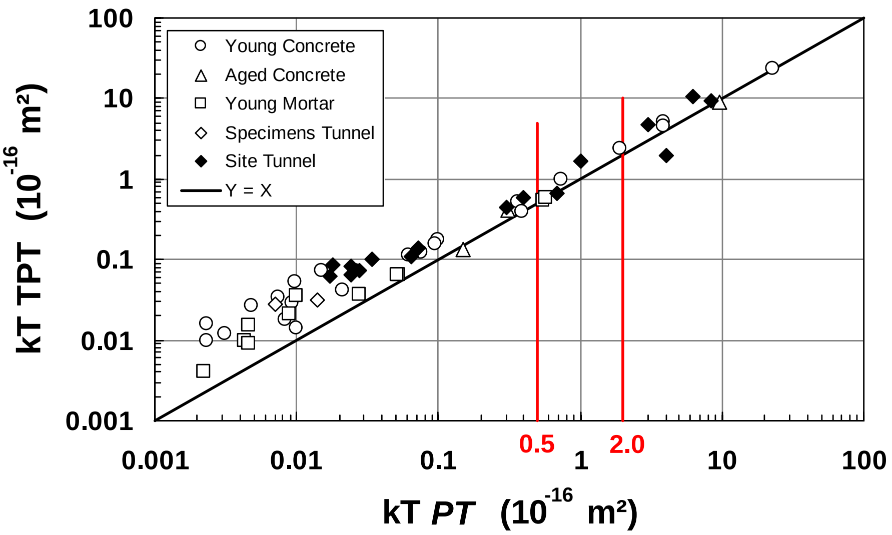


Fig. 9. “In situ” kT results obtained in the tunnel (♦) with the “Torrent Permeability Tester” (TPT) and the “PermeaTORR” (*PT*), compared with previous available laboratory test results.

8 CONCLUSIONS

The ASTRA Recommendations, Jacobs et al (2009), set the stage for the specification and control of the air-permeability on site. This will certainly have a positive effect on the durability of concrete structures in Switzerland, with the following expected benefits:

- 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.)
- All too common bad practices (uncontrolled water addition to concrete trucks, poor compaction, lack of curing, improper slabs finishing, etc.) will be eradicated
- 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 the near future.

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