Carbonation rate in old structures assessed with air-permeability site NDT

Kei-ichi Imamoto
Tokyo University of Science, Tokyo, Japan

Rui Neves
Polytechnic Institute of Setúbal, Barreiro, Portugal

Roberto Torrent
Materials Advanced Services Ltd., Buenos Aires, Argentina

ABSTRACT: In this paper, test results obtained on several old concrete structures (up to 60 years old), located in different regions of Japan, Portugal and Switzerland, are presented. First, the coefficient of air-permeability *kT* (Swiss Standard SIA 262/1) was measured at different locations of those structures, to be followed by the measurement of the carbonation depth *CD* on samples removed from the same locations. The *CD* values were "normalized" by converting them into carbonation rates *CR* (*CR* = *CD* / √*age*). The results highlight the following facts:

- There is a large scatter in both *kT* and *CD* within each structure, posing a challenge for prediction modeling
- There is a general trend of higher values of *CR* for higher values of *kT*
- If *kT* is low, *C*R is also low; however, there are some cases of high *kT* and low *CR* (possibly due to micro-climatic exposure conditions and/or presence of cracks)
- There seems to be a threshold value of *kT* (~0.01 10^{-16} m2) below which the carbonation rate is negligible (less than 1 mm/√a , i.e. less than 10 mm in 100 years)

The results presented are useful to predict the carbonation rate on the basis of non-destructive air-permeability measurements made on site, as has been done in some real cases.

1 INTRODUCTION

Although less aggressive than chloride-induced corrosion, corrosion damage due to carbonation constitutes a matter of concern. This incidence may be aggravated in the future by the gradual rise in CO_2 concentration in the air, especially in industrial, motorcar and urban environments, and by the reduction in clinker content of the binders that is taking place in the cement and concrete industry nowadays.

The carbonation progress is generally assumed as:

$$CD = CR \cdot \sqrt{t} \tag{1}$$

CD = carbonation depth (mm)
CR = carbonation rate (mm/y½)
t = time (years)

Where *CR* depends of several factors such as the “penetrability” of the concrete cover, the amount of carbonatable material in the matrix, the concentration of CO_2 in the environment, the exposure conditions (temperature, RH, rain), etc.

The “square root” rule, described by Eq. (1) is often used to estimate the service life of existing concrete structures. Indeed, measurements of the carbonation depth *CD*, obtained destructively on drilled cores or fragments removed from the surface, at time t_0 allow, by a simple application of Eq (1) to know *CR* and, therefore, to predict the time *t* at which the carbonation front will reach the steel and depassivate it (when carbonation depth *CD* equals cover depth). *CD* is typically measured by spraying a pH indicator (usually phenolphthalein) on freshly broken surfaces [RILEM, 1998].

This simple approach faces two drawbacks: the destructive or damaging nature of the measurements and the high variability of *CD*, typically encountered in a single concrete structure. Table 1 shows the wide range of *CD* found in very old structures investigated in Chile [Rojas K., 2006] and in younger structures investigated in China [Liang et al, 2013].

Table 1. Range of *CD* values measured in Chilean and Chinese structures

	CHILE			CHINA	
	Quillota Bridge	Barros Arana Bldg.	Eng. Univ. Chile Bldg.	Chorng-chin Viaduct	Wann-fwu Bridge
Built	1908	1910	1917	1971	1987
Tested	2006	2005	2005	2012	2012
Age	98	95	88	41	25
No. Tests	5	6	5	10	10
CD min	0	35	28	0	0
CD max	65	100	55	38	140
CR max	6,57	10,26	5,86	5,93	28,00

The high scatter of *CD* results is confirmed by other results presented below. As a result, in order to have an acceptable picture of the *CD* values in the structure, an unaffordable amount of concrete samples is required.

As discussed above, the "penetrability" of the cover concrete is one of the main factors governing the carbonation rate *CR*. Air-permeability is one of the most accepted properties to evaluate the "penetrability" of the cover concrete and is one of the easier tests to perform on site.

Already in the 90's, a method to estimate the progress of carbonation in concrete, based on intrusive site measurements of air-permeability, was proposed [Parrott, 1994], included also as a CEN document [Andrade et al, 1992]. Similar approaches were applied to use non-destructive air-permeability measurements to predict the service life of the emblematic Museum of Western Art in Tokyo [Imamoto et al, 2012] and of precast concrete segments of the Port of Miami Tunnel [Torrent et al, 2013]. In these two investigations the coefficient of air-permeability *kT* was measured applying the non-destructive Swiss Standard Method [SIA 262/1-E, 2013], described in the Annex.

The purpose of this paper is to review and analyze published data of parallel measurements of air-permeability *kT* and carbonation depth *CD*, conducted on old structures in Japan, Portugal and Switzerland, to explore the possibility of using the non-destructive *kT* measurements for the prediction of carbonation rate and its associated service life.

2 CARBONATION AND AIR-PERMEABILITY *kT* IN THE LABORATORY

Several laboratory investigations have shown that the coefficient of air-permeability kT correlates well with natural and accelerated carbonation of concrete.

Fig. 1 presents results of CR values (calculated as the measured CD divided by the square root of the exposure time) as function of kT measured at onset of exposure, reported by:

- [Torrent und Ebensperger, 1993], who exposed prisms made with several concrete mixes, subjected to different curing conditions, to an ambient of 20°C, 50% RH for 500 days
- [Torrent und Frenzer, 1995], who exposed prisms made with several concrete mixes, subjected to different curing conditions, to an ambient of 20°C, 50% RH for 2 years
- [Kubens et al, 2003], who exposed cubes and prisms made with two concrete mixes, subjected to different curing conditions, to an ambient of 30°C, 40% RH for 90 days. Companion specimens were also exposed to accelerated carbonation: 5% CO_2, 30°C, 50% RH for 7 days, with good correlation with kT (not included in Fig. 1)
- [Imamoto et al, 2008], who exposed panels made with three concrete mixes, subjected to two different curing conditions, to an ambient of 20°C, 60% RH for 3.5 years
- Holcim, prisms made with four concrete mixes, subjected to 28 d. moist curing, were exposed to an ambient of 20°C, 57% RH for 2 years.

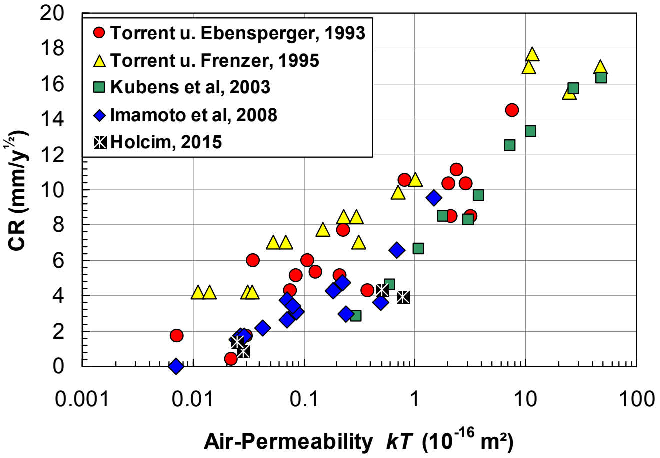

Figure 1. *CR* measured in the lab under natural CO_2 exposure vs. *kT* values

Despite the different origin of the data, the good agreement between the five sets of results is remarkable. The fact that most concretes included in Fig. 1 are made with OPC may have contributed to the good agreement.

The laboratory data show that the carbonation rate *CR* follows a linear relation with the logarithm of *kT* and that *CR* becomes negligible for *kT* values below ≈ $0.01\ 10^{-16}$ m².

3 CARBONATION AND AIR-PERMEABILITY *kT* ON SITE

3.1 *Experimental*

The general procedure was to identify suitable structures and elements where to conduct the tests. First, *kT* was measured on site, followed by cores drilling at the same spot or by fragments breaking of the concrete; the *CD* was measured by spraying a phenolphthalein solution [RILEM, 1988] on freshly broken surfaces (e.g. by splitting the cores).

The *kT* values were measured using different instruments (see Table 2): a prototype, the "Torrent Permeability Tester" (TPT), manufactured by Proceq and, more recently, the "*PermeaTORR*", manufactured by Materials Advanced Services.

A short description of the test method to measure *kT* is presented in the Annex.

3.2 *Structures Investigated*

Table 2 provides a brief description of the structures investigated; more information can be found in the corresponding references.

[Torrent u. Ebensperger, 1993], is shown at the top of the charts.

The data in Fig. 2 present a high scatter, both in terms of *CR* and of *kT*. The values of *CR* for each structure range from close to 0 up to 4, 5 and even almost 6 mm/y½, confirming the high variability of this property, already discussed in relation with Table 1.

Table 2 – Structures investigated in Switzerland, Japan and Portugal

<table>
<tr><th>Structure</th><th>Age at test (years)</th><th>Location</th><th>Country</th><th>Reference</th><th>Instrument</th></tr>
<tr><td>Motorway Underpass</td><td>30</td><td>Kanton SO</td><td rowspan="4">Switzerland</td><td rowspan="2">Torrent and Frenzer, 1995</td><td rowspan="2">Prototype</td></tr>
<tr><td>Urban Bridge</td><td>60</td><td>Basel BS</td></tr>
<tr><td>Highway Bridges</td><td>30</td><td>NW Switz.</td><td>Jacobs, 2008</td><td rowspan="2">TPT</td></tr>
<tr><td>Building</td><td>30</td><td>Canton TI</td><td>Teruzzi, 2009</td></tr>
<tr><td>Museum</td><td>50</td><td>Tokyo</td><td rowspan="6">Japan</td><td rowspan="6">Imamoto et al, 2014</td><td rowspan="6">PermeaTORR</td></tr>
<tr><td>Multi-family dwelling</td><td>49</td><td>Osaka</td></tr>
<tr><td>Specimens</td><td>12-32</td><td>Tochigi</td></tr>
<tr><td>Multi-family dwellings</td><td>42</td><td>Chiba *</td></tr>
<tr><td>HSC dummy columns</td><td>15</td><td>Tsukuba</td></tr>
<tr><td>Lab. Building,
E and W sides</td><td>49</td><td>Sendai</td></tr>
<tr><td rowspan="2">Highway Overpasses
(HW OP)</td><td>18-32</td><td>Lisbon</td><td rowspan="8">Portugal</td><td rowspan="8">Neves, 2012</td><td rowspan="8">TPT</td></tr>
<tr><td>11-31</td><td>Setúbal</td></tr>
<tr><td rowspan="2">Highway Underpasses
(HW UP)</td><td>19-32</td><td>Lisbon</td></tr>
<tr><td>11</td><td>Setúbal</td></tr>
<tr><td>Highway Pedestrian Overpass (HW POP)</td><td>4</td><td rowspan="2">Lisbon</td></tr>
<tr><td>Motorway Overpass
(MW OP)</td><td>32</td></tr>
</table>

* Lightweight Aggregates Concrete (LWAC)

3.3 *Experimental Results*

Values of carbonation rate *CR*, calculated by dividing the measured *CD* by the square root of the age at test are presented in Figs. 2, 3 and 4, as function of the *kT* measured at the same spots. Figs. 2, 3 and 4 present the results obtained on Swiss, Japanese and Portuguese structures, respectively. The qualitative scale of permeability classes, based on *kT* values

What is also remarkable is the high variability of air-permeability *kT*, which ranges over 3, 4 and 5 orders of magnitude, for each of the different structures studied.

The situation for the Japanese cases has similarities and differences (particularly if we confine the analysis only to the real structures tested). On one extreme, the Chiba buildings, built with LWAC, show CR values in the range 2 – 13 mm/y½. On the other hand, the Osaka buildings show much more uniform values of CR (1.5 – 3.5 mm/y½). The results from the Museum of Western Art in Tokyo present two well differentiated sets of data. Five results showing low values of kT and CR, corresponding to measurements conducted on repair mortars and three results with high kT and moderate CR, corresponding to the few cores allowed to be drilled from the historical building (only one designed by Le Corbusier in Japan).

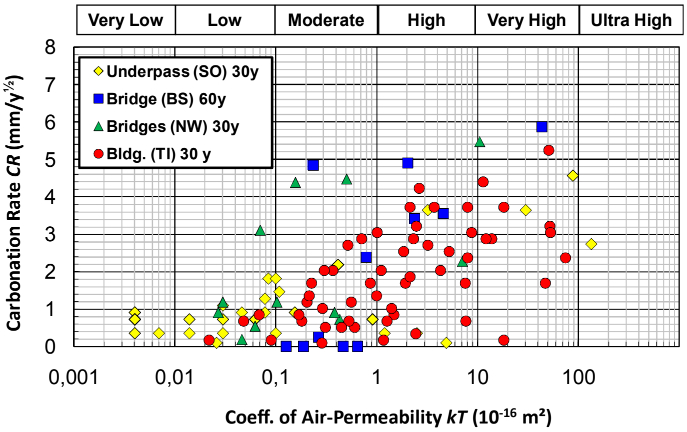

Figure 2. CR and kT values measured on Swiss Structures

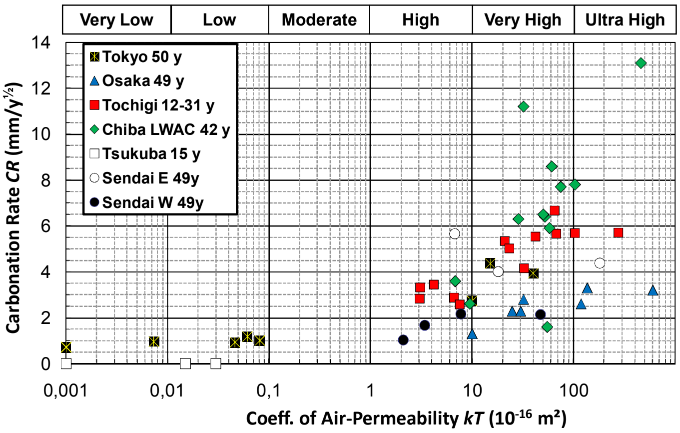

Figure 3. CR and kT values measured on Japanese Structures

The data in Fig. 4 show a similar pattern as those in Fig. 2, particularly on the upper range. However, there is comparatively scarcity/absence of very low CR values for the whole range of kT values. Perhaps the warmer and drier climatic conditions of Portugal may explain this fact.

No clear difference between the concrete structures, ages or locations can be observed in Fig. 4.

The three Figs. 2, 3 and 4 show a general trend of increasing values of CR for increasing values of kT.

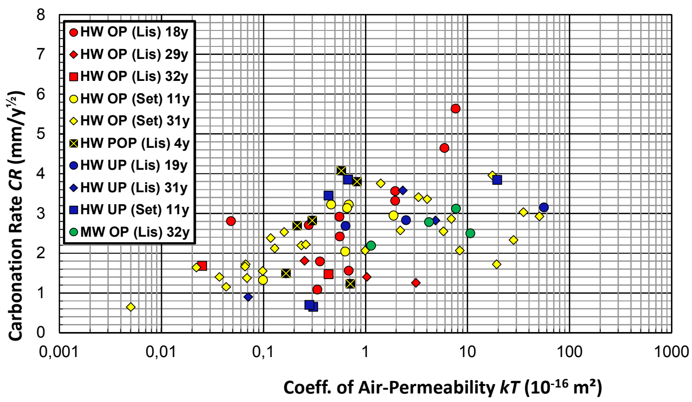

Figure 4. CR and kT values measured on Portuguese Structures

4 USE OF AIR-PERMEABILITY TESTS FOR CARBONATION PREDICTION

Fig. 5 merges the data shown separately in Figs. 2, 3 and 4, differentiating just the country where they were obtained.

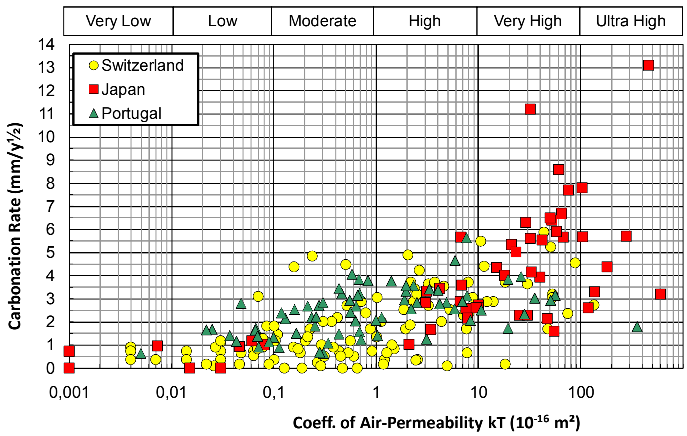

Figure 5. CR and kT values measured on Swiss, Japanese and Portuguese Structures

Fig. 5 shows that the three sets of data merge nicely, despite the different geographical and climatic regions included and the different instruments and experimental procedures applied by the five research teams involved.

Fig. 5 also shows:

a) that the carbonation rate CR tends to increase with growing values of kT
b) the confirmation of a limiting value of $kT \approx 0.01\ 10^{-16}$ m², below which CR becomes negligible, same as for laboratory tests (see Fig. 1)
c) qualitatively, it is clear that for low values of kT ($< 0.1\ 10^{-16}$ m²), there is a high certainty that the carbonation rate will be low (between 0 and 2 mm/y^{½})
d) for higher values of kT the uncertainty increases with kT, as both low and high carbonation rates can occur for a given kT value.

The phenomenon in item d) can be speculatively explained by the differences in microexposure (sunlight, rain, wind, moisture, etc.) of the different elements tested within the structures investigated, affecting carbonation rate (normally *kT* is measured under dry conditions [SIA 262/1-E, 2013]); see e.g. difference in data from E (yellow dots) and W (black dots) sides of Sendai Building in Fig. 3. Another possible source of scatter could be the effect of localized defects (e.g. microcracks) that may affect *kT* but not necessarily *CD* (see Fig. 6). In both cases, to a high *kT* value a relatively low *CD* may correspond. The presence of such cracks has not been identified/reported by the researchers, so the eventually affected data cannot be discriminated in Fig. 5.

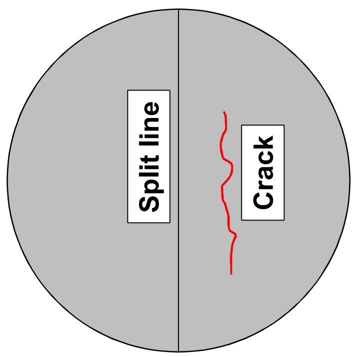

Figure 6. Possible crack affecting *kT* but not *CD* measured on the core split surface

The data shown in Fig. 5 constitute a useful platform on which a model to predict carbonation in old structures, based on non-destructive measurement of the air-permeability on site, can be built.

A probabilistic treatment may be appropriate, such as that applied by [Teruzzi, 2009] to his own data (red dots in Fig. 2). Fig. 7 shows the result of his analysis.

The plots show clearly what has been described qualitatively before: the displacement to the right (towards higher values of *CR*) of the modes of the functions for increasing *kT* values and the corresponding higher uncertainties (wider distributions).

An attempt is currently being made to combine this approach with the probabilistic distribution (due to inaccuracies) of the cover depth, measured non-destructively. If successful, it would allow establishing the probability that the service life exceeds a certain value, from the combined measurement of *kT* and the cover depth, at each point of the structure under investigation.

This opens the ground for a more realistic assessment, as the structure can be scanned extensively by both NDT methods: air-permeability test and covermeters and a mapping of service lives (at given reliability levels) could be built.

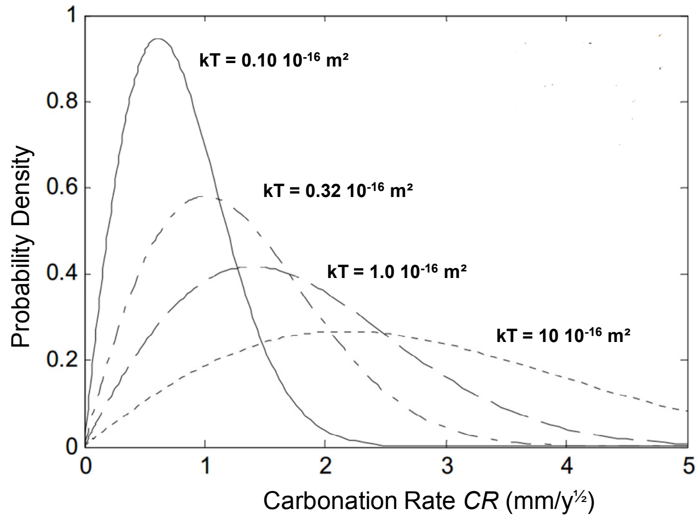

Figure 7. Change in the probability distribution of *CR* as function of *kT* [Teruzzi, 2009]

5 CONCLUSIONS

- Both the carbonation rate *CR* and the coefficient of air-permeability *kT* show a high range of values on the same structure, making the application of analytical prediction models questionable
- The coefficient of air-permeability *kT*, measured after the Swiss standard method [SIA 262/1, 2013] correlates very well with the rate of carbonation *CR,* measured in the laboratory under natural CO_2 exposure
- The correlation between *CR* and *kT* values, measured on old existing structures in Japan, Portugal and Switzerland, shows the following pattern:
  - In general terms, *CR* grows with increasing *kT* values
  - There seems to be a threshold limit of $kT \approx 0.01\ 10^{-16}$ m² below which *CR* is negligible
  - For low values of *kT* ($< 0.1\ 10^{-16}$ m²), there is a high certainty that the carbonation rate will be low (between 0 and 2 mm/y^{½})
  - For higher values of *kT* the uncertainty increases with *kT*, as both low and high carbonation rates can occur for a given *kT* value.
- The results obtained on old structures constitute a useful platform on which a model to predict carbonation in old structures, based on non-destructive measurement of the air-permeability on site, can be built
- A probabilistic treatment of data may allow establishing the probability that the service life exceeds a certain value, from the combined measurement of *kT* and the cover depth, at each point of a structure under investigation. This work is in progress at the moment.

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ANNEX: DETERMINATION OF THE COEFFICIENT OF AIR-PERMEABILITY *kT* AFTER SWISS STANDARD [SIA 262/1, 2013]

Figs. 8 and 9 show a sketch and details of the test, intended for measuring, non-destructively, the coefficient of air-permeability of the cover concrete, in the lab and on site.

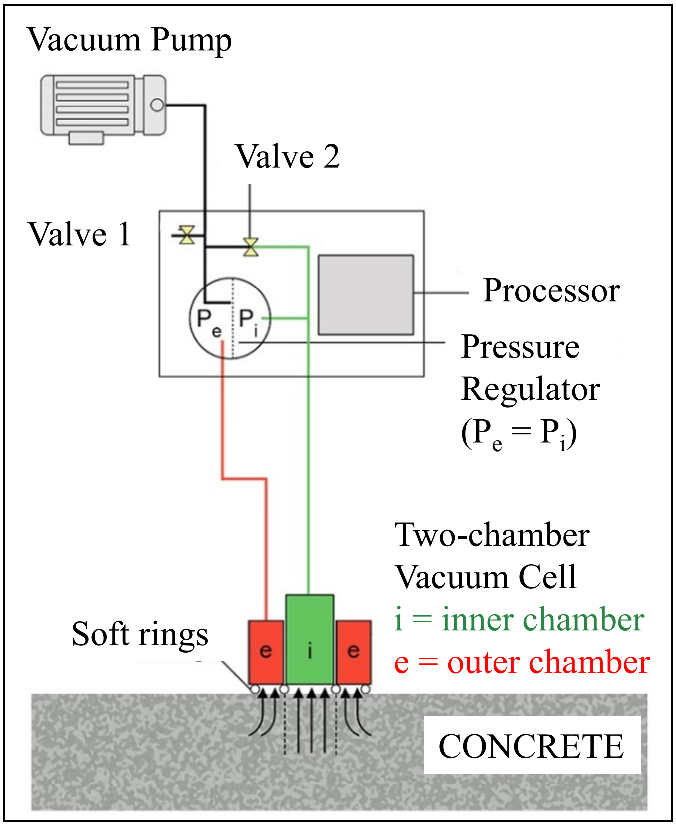

Figure 8. Sketch of *kT* test [SIA 262/1, 2013]

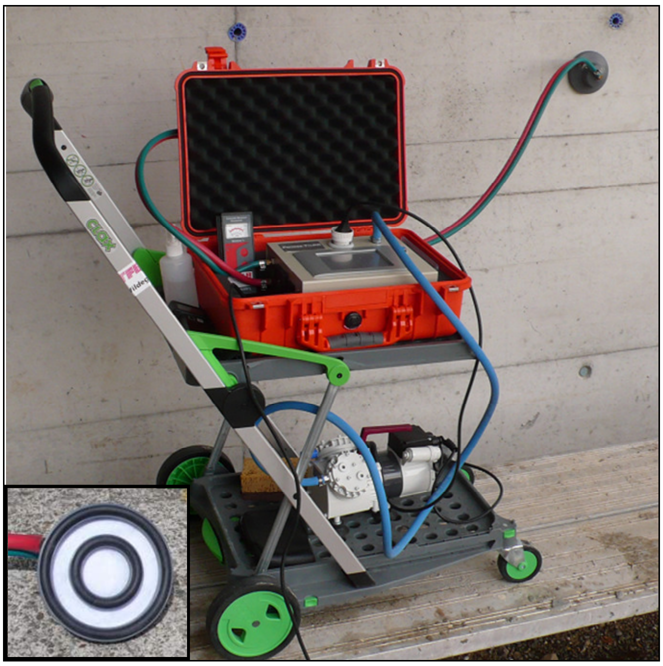

Figure 9. *kT* test: details of vacuum cell and application on a concrete wall

Vacuum is created inside the 2-chamber vacuum cell (Fig. 8), 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 in the inner chamber ΔP_i (measurement starts at t_0 = 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 (sketched in Fig. 7) and the coefficient of permeability to air *kT* (m²) can be calculated.

Valve 1 serves to reset the system by opening it to the atmospheric air.

Applying the Hagen-Poiseuille law for compressible fluids, under certain assumptions, the coefficient of air-permeability is calculated with Equation (2); a full derivation can be found in http://www.m-a-s.com.ar/eng/documentation.php.

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

kT: coefficient of air-permeability (m²)
V_c : volume of inner cell system (m³)
A : cross-sectional area of inner cell (m²)
μ : viscosity of air at 20°C (= 2.0 . 10^{-5} Ns/m²)
ε : estimated porosity of the cover concrete (default value assumed = 0.15)
P_a : atmospheric pressure (N/m²)