Real Case: Assessing Sulfate Resistance of Coastal Protection Precast Elements

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Abstract. As part of a new harbor development, a new offshore breakwater will be constructed, for which the use of coastal protection plain precast concrete elements (Accropodes^{TM} II[1]) is required. The applicable exposure class is S1 (ACI 318). Over 4'000 elements have been produced. The owner required guarantees on the sulfate resistance of the elements before accepting them for usage in the project. For this, a revision of the documentation available was conducted, complemented by a thorough field investigation, measuring the coefficient of air-permeability kT (Swiss Standard SIA 262/1) of preselected elements (damaged during transportation) and elements representing the 28 weeks of production. The site NDTs confirmed a high quality of the majority of elements that were judged fit for the purpose. However, the NDTs confirmed the questionable quality of those cast during the initial period, requiring further evaluation before acceptance.
The paper presents the results of: water aggressiveness, cement chemistry, strength quality control and air-permeability kT, and the criterion used to assess sulfate resistance of the elements.

Introduction

As part of a new harbor development, an offshore breakwater will be constructed, for which the use of coastal protection plain precast concrete elements (Accropodes^{TM} II[1]) is required. Around 4'000 elements were produced at the time of the measurement campaign carried out.

Before accepting them for usage in the project, guarantees on the sulfate resistance of the 4'000 elements produced are required. For this, a revision of the production control documentation available was conducted, as well as a visual inspection of the elements.

Due to some imperfections observed on the surface of some elements (large blowholes, water streaks, cracks), it was decided to complement that inspection with a thorough field investigation, measuring the coefficient of air-permeability kT (Swiss Standard SIA 262/1 [1]) of preselected damaged elements (damaged at the casting area during transportation) and elements representing the 28 weeks of production.

The objective of this paper is to present data on:

- aggressiveness of the water
- cement chemistry
- compressive strength of cylinders tested in the lab during production quality control

[1] *ACCROPODE™ is a trademark of ARTELIA Eau&Environnement – France and is registered in France and in a number of other foreign countries.*

- air-permeability measured "in situ" on actual elements

and, based on the analysis of the above information, to assess the suitability of the built perecast elements to perform satisfactorily in the location environment for a design service life of 50 years.

Exposure Conditions of the Elements

Aggressiveness of the Water. The facility is to be located in the mouth of a large river estuary, that brings sweet water into the sea. A profile of the salinity of the water at different depths was obtained immersing a CTD M48 probe, which measures electrical Conductivity, Temperature and Depth, at five different stations along the project location. Fig. 1 shows two out of the five obtained profiles of salinity, expressed in practical units of salinity (derived from the electrical conductivity).

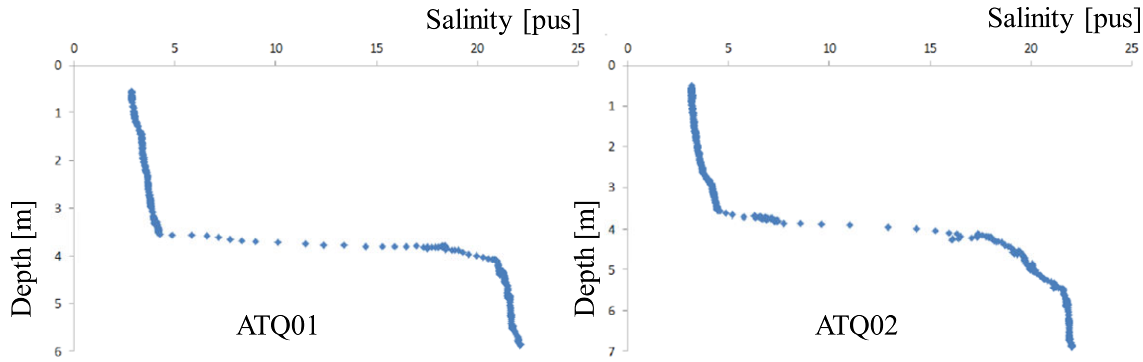

Fig. 1 - Salinity profiles obtained at two different measuring stations

Fig. 1 shows a clear stratification in the salinity of water, with a low salinity at depths up to about 3 m and a high salinity at depths beyond 4 m. This suggests that sea water, of higher density, occupies the lower strata, whilst the river water occupies the upper strata.

A chemical analysis of samples taken from both strata, confirms the variable degree of aggressiveness with depth, as shown in Table 1.

Table 1 - Relevant aggressiveness characteristics of water at different stations and depths

	Parameters measured at five different sampling stations									
	Station 1		Station 2		Station 3		Station 4		Station 5	
Depth [m]	2.0	5.5	2.0	5.5	2.0	5.5	3.0	9.0	3.0	10.0
Salinity [pus]	6.0	21.0	4.3	21.9	4.4	21.9	5.1	22.2	6.0	22.4
SO_4^{2-} [ppm]	257	1550	304	1248	304	1504	459	1294	489	1541
Cl^- [ppm]	1825	12340	2325	10337	2202	11338	3650	13187	3696	13110

Relevant Exposure Class and Requirements. The plain concrete precast elements do not contain embedded metals, which excludes steel corrosion as a possible deterioration mechanism. Therefore the main deterioration mechanism is sulfate attack of the sea water to the concrete. This case corresponds to ACI 318 [2] Exposure Class S1 ("Moderate Sulfate Attack").

To resist the S1 Exposure Class, ACI 318 specifies the following requirements for the concrete:

- a Moderate Sulfate Resistant Cement
- $w/c_{max} = 0.50$ and $f'c_{min} = 28$ MPa (measured on cylinders)

In our particular case, the precast elements were built with an Ordinary Portland Cement. ASTM C150 standard [3] specifies, for "Moderate Sulfate Resistance Cement", a maximum value of the C_3A content of 8%. The C_3A content is calculated from the oxide cement composition as:

$$C_3A\ (\%) = 2.65 \cdot Al_2O_3\ (\%) - 1.692 \cdot Fe_2O_3\ (\%) \quad (1)$$

Compliance with ACI 318 Requirements for S1 Exposure Class

Cement Type. The cement used for manufacturing the precast eleements is an Ordinary Portland Cement. A total of 58 cement producer's certificates were revised, covering the entire production period, focusing in particular on the C_3A content, to check its Sulfate Resistance. Fig. 2 shows the variation in C_3A of the 58 samples.

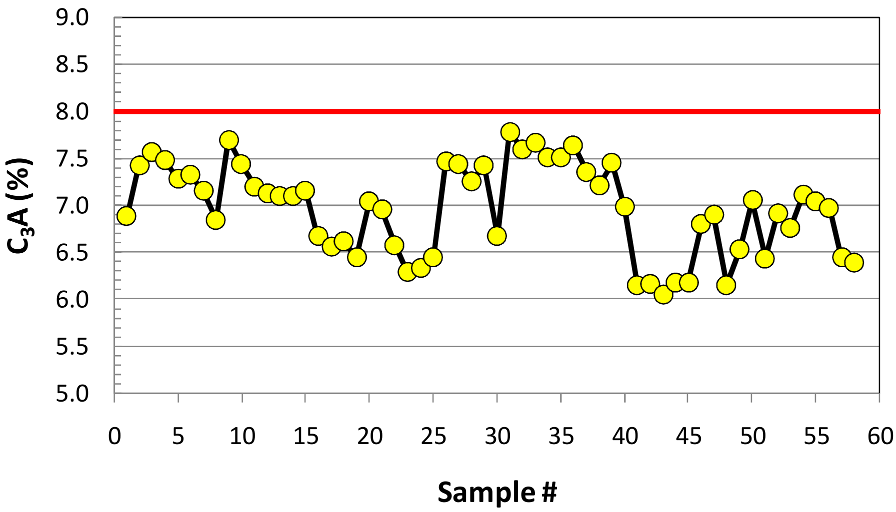

Fig. 2 - Variation of C_3A content of 58 cement samples

The analysis shows that the C_3A content of the cement is systematically below 8%. Therefore, the cement used to build the precast elements corresponds to Type II (ASTM C150 [3]), "Moderate Sulfate Resistance". Hence, it fulfills the requirements for ACI Exposure Class S1.

Mix Design: w/c Ratio and Strength. The mix design of the concrete used to build the precast elements was declared in a document issued by the ready-mixed concrete supplier, validated by the Quality Assurance and Control authority.

According to that document, the concrete has the following main characteristics:

- Cement Content: 400 kg/m³
- water/cement ratio: 0.38
- f'c: 40 MPa, for 5% lower fractile
- Maximum size of aggregate: 20 mm
- Slump: 170±30 mm

According to the declared characteristics, the concrete mix complies with the requirements of maximum w/c = 0.50 and minimum specified strength of 28 MPa, for ACI 318 Exposure Class S1.

Concrete Strength. Fig. 3 presents 1129 records of 28-day compressive strength results, measured on Ø150x300 cylinders cast during the entire production.

The overall mean strength is 52.8 MPa, with a rather high standard deviation of 7.7 MPa; the minimum value of strength recorded was 21.5 MPa.

What can be seen in Fig. 3 is an initial period of about 6 weeks of extremely variable strength results, not complying with the declared strength class of 40 MPa, nor with the minimum specified strength of 28 MPa required by ACI 318 for S1 Exposure Class. The red line indicates the absolute minimum level of strength for each individual result accepted by ACI 318; it can be seen that several values fall even below that line.

The results from production month 3 onwards show a lower variability. The 951 test results obtained after that date show a mean strength of 54.8 MPa and a standard deviation of 4.8 MPa, which yields a characteristic strength (5% fractile) of 46.9 MPa, in conformity with the mix design strength declared of 40 MPa. Just 3 out of the 951 test results have strengths below 40 MPa, i.e. 0.3%. Conformity with the strength requirements for S1 Class (f'c ≥ 28 MPa) is comfortably achieved.

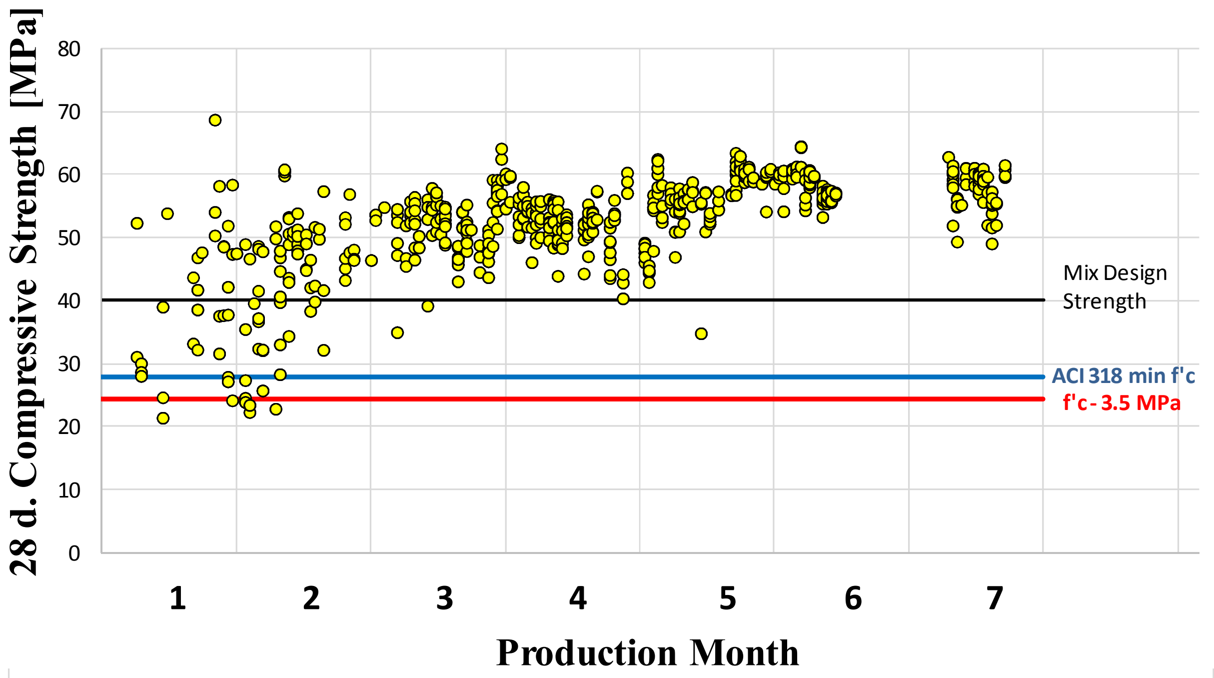

Fig. 3 - 28-day Compressive Strength of 1129 concrete samples

Compliance Assessment. Regarding conformity of the concrete produced with the ACI 318 requirements for S1 Exposure Class, the following can be concluded:

- The cement used corresponds to Type II ASTM C150, in conformity with the requirements
- The declared water/cement ratio of 0.38 is below the maximum of 0.50 specified, in conformity with the requirements
- The characteristic strength of the concrete of 46.9 MPa complies with the minimum of 28 MPa specified
- However, given the low results and high variability recorded till the end of the second month of production, compliance can only be awarded to the concrete produced after that date

Visual Inspection of the Cast Elements

Compliance of the concrete produced by the ready-mixed concrete supplier is not enough to ensure the performance of the precast elements.

Indeed, inadequate compaction, insufficient moist curing, cracks and other defects may impair the permeability of the concrete elements, which is widely regarded as the key factor for the durability of concrete exposed to seawater attack [4, 5].

A visual examination of the precast elements was conducted and reported. The main surface defects detected were blowholes, some of them relatively large, resulting from the impossibility of air bubbles to escape during vibration, especially along top inclined surfaces of the metal forms (see the complex shape and large size of the Accropodes^{TM} II in Fig. 4; each element fits exactly inside a 2.17 m cube and have ≈ 3 m³ of volume). Some cracks and water streaks were also observed.

Site Air-Permeability Testing

The visual inspection left some doubts on the extent to which the defects found may affect the performance of the elements. In order to verify that, a program of tests was established to measure the coefficient of air-permeability kT directly on a sample of the precast elements produced. This test method was chosen, given its good correlation with water sorptivity and penetration of water under pressure (EN 12390-8) [6], relevant properties for the case under consideration.

Test Method. The air-permeability measurements were conducted according to the prescriptions of Swiss Standard SIA 261/1 [1] using the *PermeaTORR* instrument (see description in the Annex). In particular, the instrument was conditioned and calibrated before initiation of the measurements. The surface moisture was measured with an impedance-based instrument, Tramex CMEX 1210, to check that it did not exceed 5.5%, as required in [1].

Preliminary Trial. A preliminary trial was made on two companion precast elements (C454 and C455), cast on the same day. These units had been stored separately and covered with canvas, because one of them was partially broken during transportation, the companion being intact.

A total of 10 and 13 measurements were performed on each element, to investigate their homogeneity. Care was taken to avoid that the rings of the instrument's vacuum cell (see Annex) "shortcut" blowholes. Fig. 4 shows the pre-selected Accropodes^{TM} II, with the broken one at the front; Fig. 5 shows the location of some tests (holes correspond to core drilling locations).

Fig. 4 - Preselected Accropodes^{TM} II (broken element at the foreground) ready for testing

Fig. 5 - a) Tests performed on broken element *b) Test on companion element*

Neither the location of the measurements nor the presence of blowholes showed a clear effect on the measured values. In fact, the lowest kT values for both elements were obtained for tests made directly on blowholes. This indicates that "per se", the blowholes do not have a detrimental effect on the permeability and potential durability of the elements.

The results of the preliminary trials indicate that the quality of both precast elements is very similar, in terms of central value (kT_{gm}) and uniformity (sLOG)[2], as shown in the bottom part of Fig. 6, discussed below. The permeability of both precast elements can be judged as "Moderate" (see classification at top of Fig. 6).

Field Measurements on Sampled Elements. A sample of 28 precast elements was selected, one for each week of manufacturing. On each element, 3 measurements were performed: on top, on the nose and on the bottom, as cast. The elements were separated into Lots of about 1000 elements each (A, B, C and D in chronological order).

The results obtained on the 28 precast elements tested are plotted in Fig. 6, in a format that presents in logarithmic scale, for each element, the value of kT_{gm} (black dots) and a bar representing $kT_{gm} \pm$ sLOG. For comparison, the values of the preliminary trial are also plotted at the bottom.

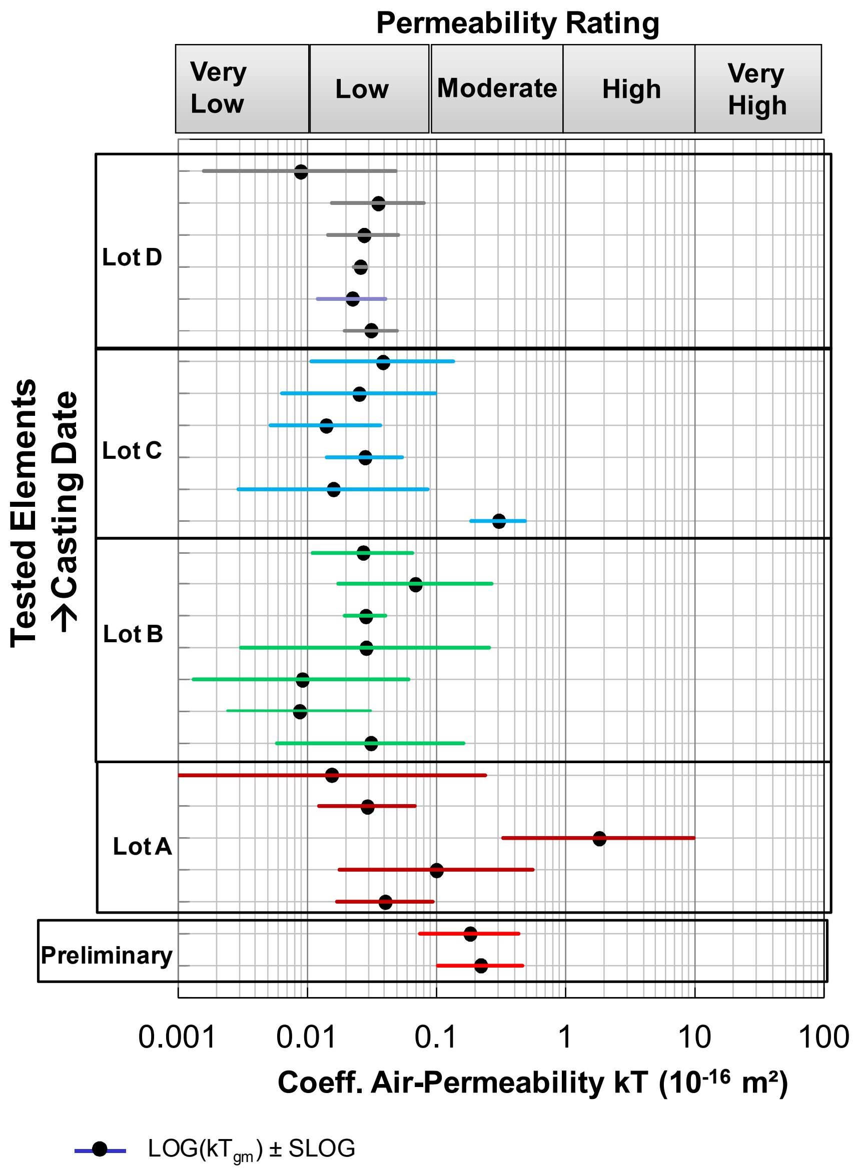

Fig. 6 - Mean and scatter of results obtained on the Accropodes™ II tested

It can be seen that the kT_{gm} of most elements fall within the "Low" Permeability Class, with a few falling in the "Very Low", "Moderate" and "High" Permeability Classes.

[2] It has been shown that kT follows a log-Normal distribution, hence the statistical test parameters adopted are the geometric mean (kT_{gm}) and the standard deviation of $\log_{10}kT$ (sLOG)

The elements belonging to Lot A (those made at the initial stages) show higher and more scattered kT_{gm} values. Actually, the uniformity in kT_{gm} values increases with the date of casting (bottom to top). This is in line with the level and scatter of early strength results shown in Fig. 3.

Assessment based on Swiss Specifications. Swiss Standard SIA 262/1 [1] indicates limiting values of site air-permeability kT_s, for concrete types associated with exposure classes (and their combinations) typically found in the country, as shown in Table 3. kT_s is an "upper" characteristic value that can be associated to a 16% "defective" fractile.

The X classes correspond basically to those defined in EN 206 [7]. Unfortunately, Switzerland being a landlocked country, none of the exposure classes in Table 3 corresponds to seawater exposure. However, we can see that the maximum w/c ratio for Concrete Types C, D and E is 0.50, i.e. the same specified by ACI 318 for sulfate resistance of concrete exposed to seawater. Therefore, assuming same w/c ratio → same permeability, we can assimilate the recommended site kT_s value for those Concrete Types ($kT_s = 2.0\ 10^{-16}$ m²) to that required for concrete elements to achieve the same 50 years service life, when exposed to sulfate attack by seawater.

Table 3 - Indicative values for evaluation of air-permeability measurements

	Concrete Types						
	A	B	C	D	E	F	G
Strength Class	C25/30	C25/30	C30/37	C25/30	C25/30	C30/37	C30/37
Exposure Classes (CH)[3]	XC1 XC2	XC3	XC4 XF1	XC4 XD1 XF2	XC4 XD1 XF4	XC4 XD3 XF2	XC4 XD3 XF4
Minimum Cement [kg/m³]	280	280	300	300	300	320	320
Maximum w/c ratio	0.65	0.60	0.50	0.50	0.50	0.45	0.45
Recommended kTs [10^{-16} m²]	-	-	2.0	2.0	2.0	0.50	0.50

Hence, the durability of the precast elements was judged by checking conformity with a specified value of $kT_s = 2.0\ 10^{-16}$ m².

The recorded test results showed that just 2 out of 72 kT results exceed the $2.0\ 10^{-16}$ m² value, both obtained on the same element. Indeed, only 9 out the 72 individual kT results (12.5%) exceed $0.20\ 10^{-16}$ m², i.e. one order of magnitude (or Permeability Class) lower than the specified value.

Conclusions

Regarding the sulfate resistance of the Accropodes™ II, the following conclusions can be drawn:

1. The durability requirements for concrete exposed to sulfates from seawater are those specified for Exposure Class S1 (Moderate Severity) of ACI 318 [2]
2. The cement used for preparation of the concrete corresponds to ASTM C150 Type II ("Moderate Sulfate Resistant"), is in compliance with ACI 318 for Class S1
3. The reported w/c ratio of the mix design of 0.38 is well below the maximum specified in ACI 318 for Class S1 (0.50)
4. The reported 28-day compressive strength results obtained from the third month of production onwards comply with the requirements of $f'c_{min} = 28$ MPa and with the design f'c of 40 MPa
5. The site air-permeability of the precast elements belonging to Lots B, C and D comfortably comply with the limiting value of Swiss Standard SIA 262/1 [1] of $kT_s = 2.0\ 10^{-16}$ m². corresponding to mixes with w/c_{max}=0.50, hence applicable to sulfate attack from seawater
6. Given that the results of the concrete specimens tested at the initial phases of the production show a high variability in strength that do not always comply with f'c = 28 MPa (let alone 40 MPa) and that the corresponding precast elements (belonging to Lot A) showed higher and more scattered kT values, the suitability of the precast elements produced during that period is questionable

7. Therefore, Accropodes™ II produced from the third month of production onwards can be used with confidence that they will perform well under the planned exposure conditions
8. The Accropodes™ II produced during the first and second month of production may not have sufficient mechanical strength nor durability to perform adequately. Unless more detailed investigation on the actual mechanical strength and permeability of elements produced before that date demonstrate their suitability, they should not be used in the project

References

[1] Swiss Standard SIA 262/1:2013, "Concrete Structures – Supplementary Specifications", (in German and French). Annex E: 'Air-Permeability on the Structure'

[2] ACI 318M-11, "Building Code Requirements for Structural Concrete", Sept. 2011, 510 p.

[3] ASTM C150/C150M-12, "Standard Specification for Portland Cement", 2012, 9 p.

[4] Mehta, P.K., Monteiro, P., "Concrete: Microstructure, Properties and Materials", 1st Ed., 2001

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[6] Torrent, R. and Ebensperger, L., "Measurement of the air permeability of concrete 'in situ': status quo", ICCRRR 2012, Cape Town, South Africa, 2-5 September 2012.

[7] EN 206:2013, "Concrete - Specification, performance, production and conformity", Dec. 2013

Annex: Brief Description of Air-Permeability Test Method [1,6]

Vacuum is created inside the 2-chamber vacuum cell (Figs. 7 and 8), which is sealed onto the concrete surface by means of a pair of concentric soft rings, creating two separate chambers. At 60 sec 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 recorded rate of pressure rise ΔP_i with time 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) ensuring a controlled unidirectional flow into the inner chamber (Fig. 8). More details can be found in [6].

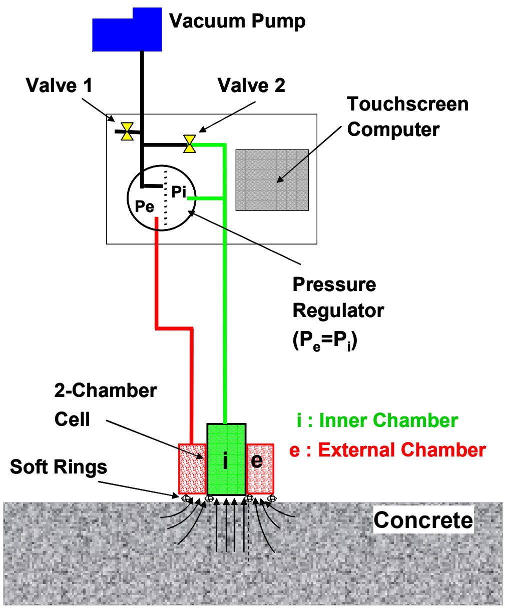

Fig. 7 – Sketch of air-permeability test.

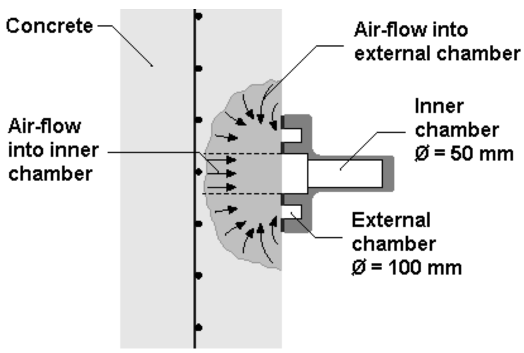

Fig. 8 –Vacuum cell and air-flow into both chambers.