Recommendation of RILEM TC 189-NEC: 'Non-destructive evaluation of the concrete cover'

Comparative test - Part I - Comparative test of 'penetrability' methods

Prepared by M. Romer

Empa, Swiss Federal Laboratories for Materials Testing and Research, CH-8600 Dübendorf, Switzerland

The text presented hereunder is a general draft for general consideration. Comments should be sent to the TC Chairman Dr. Roberto Torrent, HOLCIM Group Support Ltd., Concrete and Aggregates Division, Im Schachen, CH-5113 Holderbank, Switzerland; Tel: +41 58 858 67 14; Fax: +41 58 858 67 09; Email: roberto.torrent@holcim.com, by 30 June 2006.

TC membership – Chairman: R. Torrent, Switzerland; **Secretary:** L. Fernández Luco, Spain; **Full Members:** M.G. Alexander, South Africa; C. Andrade, Spain; M.P.A. Basheer, United Kingdom; H. Beushausen, South Africa; M. Fischli, Switzerland; A. Gonçalves, Portugal; F. Jacobs, Switzerland; J. Kropp, Germany; R. Duarte Neves, Portugal; J. Podvoiskis, United Kingdom; R. Polder, Netherlands; M. Romer, Switzerland; **Corresponding Members:** J.-P. Balayssac, France; Y. Ballim, South Africa; K. Baumann, Switzerland; J. Bickley, Canada; D. Breyse, France; E. Brühwiler, Switzerland; M. Geiker, Denmark; D. Hooton, Canada; F. Moro, Switzerland; A. Morotti, Italy; L. Nilsson, Sweden; I. Wasserman, Israel.

SCOPE OF THE TC AND AIM OF THE COMPARATIVE TEST

The subject matter of TC 189-NEC is:

- a) Selection of suitable non-destructive test (NDT) methods for the evaluation of the thickness and quality of the concrete cover ('covercrete'), in view of the durability of concrete structures
- b) Draft recommendations for the application of those test methods
- c) Establish guidelines for the specification of the quality and thickness of the concrete cover, as function of exposure conditions and service life design, and for its compliance control "in situ" by NDT methods.

The work is focused on "in situ" NDT methods. By this it is understood methods that can be applied directly on the finished structure, without introducing damage to the concrete surface. Methods that involve just slight damage, like small holes, spots or scars, to the surface are also considered.

Methods relying on the drilling of cores and testing them in the laboratory will be out of the scope of the TC's work, except as Reference tests for the NDT.

Regarding the evaluation of the quality of the concrete cover, the work focuses on methods that measure the transport of mass within the 'covercrete', including:

1. Permeability to gases
2. Permeability to water, including capillary suction
3. Ion diffusion and migration, including electrical conductivity.

Within the scope of the TC, a Comparative Test was designed and executed, with the aim of comparing the performance of different NDT instruments. The results of that test were analyzed and discussed within the TC and a final report was approved. The following papers have been extracted, by the respective authors, from that final report.

1. OBJECT OF THE EXPERIMENT

The object of the experiment was to determine whether the NDT methods designed to measure on site the "penetrability" of the concrete cover are capable to detect differences in the w/c ratio and curing conditions of concretes. The capability of the test methods is checked by applying them under standard conditions (20°C and 70% RH), as well as under "moist" conditions (20°C and 90% RH) and under "cold" conditions (10°C).

Table 1 – Test conditions investigated in the Comparative Test										
Test condition	1	2	3	4	5	6	7	8	9	10
w/c	0.40	0.55	0.60	0.40	0.55	0.55	0.40	0.55	0.40	0.55
Cement type	OPC			BFSC		OPC				
Moist curing [days]	7					1	7			
Temperature [°C]	20								10	
Moisture condition	dry						moist		dry	

2. SPECIMENS AND MATERIALS

Forty slabs (0.3x0.9x0.12 m) were cast at Empa, four for each of the test conditions shown in Table 1. Details on the composition and properties of the mixes, the casting, curing and storage of the slabs, as well as the preparation and preconditioning of drilled cores and specimens, can be found in Annex A.

The age of the slabs at the initiation of the application of the NDT comparative tests, which lasted 5 days, ranged between 54 and 69 days.

In a second stage, cores were drilled from the slabs, cut to size, dried at 50°C, weighed and shipped to LNEC for testing (another set was shipped to the Univ. of Cape Town for the determination of their Durability Indices; these results are not discussed in this paper); more details can be found in annex A. The tests conducted at LNEC on those specimens, applying standardized or RILEM-recommended tests, under controlled laboratory conditions, are referred to as "Reference Tests".

The range of ages of the specimens at the initiation of the Reference Tests, ranged between 110 and 194 days.

Both during the application of the NDT directly on the slabs as well as of the Reference Tests on the cores, the identity of the samples was coded. So, the tester did not know to which test condition the specimens belonged.

3. METHODS

3.1 "Penetrability" NDT applied

Table 2 shows the properties measured, the NDT methods applied on the slabs, the Institute that performed each test and the typical number of readings per Test Condition. A brief description, taken from [1], of the methods is given in annex B.

3.2 Reference Test methods

Table 3 shows the properties measured by the "Reference Tests" conducted at LNEC (P), quoting the standards/RILEM Recommendations followed for the tests.

3.3 Criteria to evaluate the results

The results discussed in this report are presented in annex C, Table C1 (Site Tests) and Table C2 (Reference Tests).

Table 2 - NDT applied on the slabs			
Property measured	Test method	Participant	Readings per test condition
Gas-permeability	Autoclam Air	Queens' Univ. Belfast (UK)	3
	Torrent Permeability Tester	TFB (CH) # IETcc (E)	6 8
	Hong-Parrott	LNEC (P)	4
Water sorptivity	Autoclam Water Sorptivity	Queens' Univ. Belfast (UK)	3
Electrical Resistivity	Wenner	TNO (NL)	20

The results of both laboratories being quite similar, only those from TFB are considered in this paper.

Table 3 - Reference Tests on cored samples			
Property measured	Test method	Ref.	Readings per test condition
O ₂ -Permeability	RILEM TC 116-PCD	[2]	4
Water Absorption Rate	RILEM TC 116-PCD		4
Electrical Resistivity	RILEM TC 154-EMC	[3]	4
Chloride "Penetration"	ASTM-C1202	[4]	4
Chloride "Diffusivity"	NT BUILD 492: 1999	[5]	4

3.3.1 Significance of the tests

This evaluation aims at establishing whether the test methods are capable to differentiate the "penetrability" of concretes of different w/c ratios (sets 1-2-3 for OPC and 4-5 for BFSC), of the same w/c ratio but different curing (sets 2-6) and of different w/c ratios for measurements conducted on moist slabs (sets 7-8) and on slabs that were kept for one week in a cold room (sets 9-10).

The capability of the methods is tested applying a Student's t-statistical test of the difference between the means of the pairs of sets of results under comparison, as

Table 4 – Compared sets and expected “penetrability” rating							
Compared sets	1 – 2	2 – 3	1 – 3	4 – 5	2 – 6	7 – 8	9 – 10
Rating	2 > 1	3 > 2	3 > 1	5 > 4	6 > 2	8 > 7	10 > 9
Variable tested	w/c OPC		w/c BFSC		curing	w/c moist	w/c cold

shown in Table 4. The null hypothesis H_0 is that both sets of results come from populations having the same mean “penetrability”. The alternative hypothesis H_1 is that one set has a mean “penetrability” higher than the other as indicated in the “Rating” row of Table 4, for which a one-tailed test is applicable.

The outcome of the Statistical test is evaluated as follows:

- If the result of the statistical test allows to reject the null hypothesis H_0 at a level of significance < 1%, the differentiation capability of the test, for the particular sets compared, is “highly significant” (++).
- If the result of the statistical test allows us to reject the null hypothesis H_0 at a level of significance between 1% and 5%, the differentiation capability of the test, for the particular sets compared, is “significant” (+).
- If the result of the statistical test does not allow us to reject the null hypothesis H_0 at a level of significance of 5%, the differentiation capability of the test, for the particular sets compared, is “not significant” (o).
- If the results are in reverse order than expected, the response of the test is “wrong” (--).

3.3.2 Correlation between Site and Reference Tests

This evaluation aims at establishing how well the results obtained by the Site Tests correlate with the results of the corresponding relevant Reference Tests. The “goodness” of the correlation is measured by the correlation coefficient R , for the 10 pairs of values corresponding to the 10 Test Conditions investigated. The X values are the averages obtained by the Reference Test for each test condition, and the Y values are the corresponding averages obtained by the Site Test.

The R values were calculated under two assumptions: A linear (L) regression exists between both methods ($Y=aX+b$), or a power (P) regression exists between both methods ($Y= a \cdot X^b$). The highest of the two values $R(L)$ or $R(P)$ is reported.

The correlations presented correspond to tests governed by similar transport mechanisms, e.g. permeability (gas-permeability and water suction) or ion electromigration (electrical resistivity/conductivity and chloride “diffusivity”).

3.3.3 Influence of moisture and temperature

The approach followed to evaluate the influence of moisture and temperature on the response of the Site Tests is simply to plot the average results obtained at 20°C on “dry” slabs (“normal”) against the w/c ratio, together with the results on the moist slabs (“moist”)

and at 10°C (“cold”). By looking at the graphs a qualitative evaluation can be made on how the values are affected by the change of conditions. This issue merits a more detailed investigation, which might be included in the work of a future TC.

4. RESULTS

4.1 Characteristics of the concretes

The characteristics of the concretes produced for the Comparative Test are given in Table A1 of annex A.

4.2 Results of Reference Tests

Table 5 summarizes the significance of the Reference Tests conducted at LNEC.

4.3 Results of Site Tests

The results of the Site Tests will be analysed in three different groups, representing two different transport mechanisms:

- Fluids under pressure gradients:
 - Permeability to gases (under pressure or a vacuum)
 - Water sorptivity (water under capillary suction)
- Movement of ions under an electrical field:
 - Ions electromigration (electrical resistivity)

The performance of each test method is analysed in terms of its significance (the degree of significance with which it is capable to differentiate the various “covercrete” qualities) and of the degree of correlation with the relevant Reference Tests.

4.3.1 Gas permeability

Table 6 summarizes the significance of the following gas-permeability Site Tests applied on the slabs: Autoclam, Parrott and Torrent Permeability Tester (TPT). Figs. 1a to 1f show the correlations existing between the Gas-Permeability Site Tests and the Reference Tests (O_2 -Permeability and Water Absorption Rate).

Table 5 - Significance of Reference Tests (LNEC)							
Compared sets	1 - 2	2 - 3	1 - 3	4 - 5	2 - 6	7 - 8	9 - 10
Expected penetrability rating	2 > 1	3 > 2	3 > 1	5 > 4	6 > 2	8 > 7	10 > 9
Reference Test	Differentiation capability						
O_2 -permeability	++	++	++	++	++	++	++
Water Absorption Rate	++	++	++	++	++	++	++
Electrical Resistivity	++	++	++	++	--	++	++
ASTM Chloride "Penetration"	++	++	++	++	++	++	++
NT Chloride "Diffusivity"	++	++	++	+	++	++	++

Table 6 - Significance of the Site Tests							
Compared sets	1 - 2	2 - 3	1 - 3	4 - 5	2 - 6	7 - 8	9 - 10
Rating	2 > 1	3 > 2	3 > 1	5 > 4	6 > 2	8 > 7	10 > 9
Gas-Permeability							
Differentiation capability							
Autoclam	--	++	++	0	++	++	++
Parrott	0	++	++	++	+	++	++
TPT	++	++	++	0	++	++	++
Water Sorptivity							
Differentiation capability							
Autoclam Index	++	0	++	+	++	+	++
Electrical Resistivity							
Differentiation capability							
Wenner	++	--	++	++	--	++	++

air in a cavity), which were not conducted during this investigation.

4.3.2 Water sorptivity

Table 6 summarizes the significance of the Autoclam Test (Water Sorptivity Index). Figs. 2a and 2b show the correlations existing between the Water Sorptivity Index and the Reference Tests (O_2 -Permeability and Water Absorption Rate).

4.3.3 Electrical resistivity

Table 6 summarizes the significance of the Wenner method applied on the slabs. Figs. 3a and 3b show the correlations existing between the Electrical Resistivity (Wenner) Site Test and two Reference Tests (Electrical Resistivity and Chloride "diffusivity"). As the "penetrability" is expected to be directly linked to the electrical conductivity, the latter is used for the correlations (conductivity = 1 / resistivity).

4.3.4 Influence of moisture and temperature on Site Tests

To have an indication of the temperature and degree of saturation in the slabs used for the different Test Conditions, measurements of Temperature and Relative Humidity were performed inside drilled holes, sealed to create a cavity, both by LNEC and QUB. For Test Conditions 1-6 ("dry" conditions) the relative humidity ranged between 78 and 85% whilst for 7 and 8 ("moist" condition), it ranged between 90 and 92%. The temperature reflected closely that of the room where the slabs were stored.

Figs. 4a to 4c show the effect of the moisture and temperature of the slabs on the Site Test for gas-permeability. Figs. 5 and 6 are similar but for water sorptivity and electrical conductivity, respectively.

4.3.5 Practical aspects

During the application of the Site Test methods in the Comparative Tests, several practical aspects were monitored by an independent observer, namely:

- Activities and time required to conduct the Site Test.

Fig. 1 - Correlation between gas-permeability Site Tests and Reference Tests: 1a) Autoclam-Air vs. O_2 -Permeability; 1b) Autoclam-Air vs. Water Absorption Rate; 1c) Parrott vs. O_2 -Permeability; 1d) Parrott vs. Water Absorption Rate; 1e) Torrent Permeability vs. O_2 -Permeability; 1f) Torrent Permeability vs. Water Absorption Rate.

It has to be mentioned that for Autoclam, only the results of test conditions 1 to 6 are included in the correlations, as the application of this method under test conditions 7 to 10 requires additional measurements (temperature and RH of the

Fig. 2 - Correlation of Water Sorptivity Site Test and Reference Tests: 2a) Water Sorptivity Index vs. O_2 -Permeability; 2b) Water Sorptivity Index vs. Water Absorption Rate.

Fig. 3 - Correlation between Electrical Resistivity (Wenner) Site Test and Reference Tests: 3a) Electrical Conductivity (Wenner) vs. Electrical Conductivity (LAB); 3b) Electrical Conductivity (Wenner) vs. Chloride "Diffusivity".

Fig. 4 - Effect of moisture and ambient temperature on the Gas-Permeability Site Tests: 4a) Autoclam-Air Permeability Index; 4b) Parrott K; 4c) Torrent Permeability kT.

- The impact the test has on the concrete surface (damage, stains, etc.).
- Resources required (no. of operators and dedication, electric power, weight of handling).

The result of that work is summarized in Table D1 of annex D. More details will be available in [1]. Note that the duration covers the number of readings required to assess the "penetrability" of a given test condition, as indicated for each method in Table 2.

5. DISCUSSION

5.1 Significance of Reference Tests

The results of the Reference Tests are very consistent (see Table 5). In most cases, the five tests applied (O_2 -

Fig. 5 - Effect of moisture and ambient temperature on Autoclam Water Sorptivity Index.

Fig. 6 - Effect of moisture and ambient temperature on Electrical Conductivity (Wenner).

Permeability, Water Absorption Rate, Electrical Resistivity, Chloride "Penetration" and Chloride "Diffusivity") managed to differentiate at the highly significant level the changes in w/c ratio (for both the OPC and the BFSC) and curing.

5.2 Significance and Correlation of NDT

5.2.1 Gas permeability

Table 6 indicates that the gas-permeability Site Tests were capable to significantly differentiate the qualities of the covercrete in 5 (Autoclam) and 6 (Parrott and TPT) out of 7 compared sets. Neither Autoclam nor Parrott were capable to differentiate between the concretes with w/c ratios 0.40 and 0.55 made with OPC. In the case of Autoclam, the averages are in the reverse order than expected (higher permeability for the concrete with w/c = 0.40). In the case of Parrott, the averages are in the correct order, which indicates that a larger number of readings might have made the difference significant.

None of the surface methods (Autoclam and TPT) found a significant difference between the concretes with w/c ratios 0.40 and 0.55 made with BFSC. In all cases, the averages were in the correct order, but the difference was not large enough to make it significant. This suggests that a larger number of readings might have made the difference significant.

Regarding correlation with the Reference Tests (Figs. 1a to 1f), we can say that both Parrott and TPT present excellent correlations with the RILEM-Cembureau O_2 -Permeability and also (albeit to a slightly lesser extent) with the Water Absorption Rate Reference Tests. The results of Autoclam are not as good, to some extent due to a possible underestimation of the permeability of the concrete with w/c = 0.60.

Regarding the influence of moisture and temperature (Figs. 4a to 4c), the most sensitive test seems to be Autoclam and the least sensitive seems to be TPT.

5.2.2 Water sorptivity

Table 6 indicates that the Autoclam Water Sorptivity Index was capable to significantly differentiate 6 out of the 7 compared sets.

The correlations of water sorptivity with the related Reference Tests (Figs. 2a and 2b) were relatively poor and clearly worse than those found when the same instrument was used to measure air-permeability. Against expectations, this also happened for the correlation with the Water Absorption Rate Reference Test (compare Figs. 1b and 2b).

Water sorptivity Indices seem strongly affected by the moisture content of the slabs (Fig. 5).

5.2.3 Electrical resistivity

As shown in Table 6, the Wenner Site Test method detected significant differences in 5 out of the 7 sets compared, although both failures correspond to averages in the reverse order. The correlations of the Wenner Site Tests with the Reference Tests (Figs. 3a and 3b) showed a very good correlation with the Electrical Resistivity Reference Test method and a poorer one with the Chloride "Diffusivity" Reference Test. However, these correlations are strongly and positively affected by the results of the two concretes made with BFSC (sets 4 and 5). Without them, the correlation coefficients are almost halved.

Finally, as shown in Fig. 6, the Electrical Resistivity Site Test is affected by high moisture and low temperature in the expected way (higher and lower conductivity, respectively).

6. CONCLUSIONS AND FURTHER STEPS

A summary of the quantitative recorded aspects of the performance of the test methods is presented in Table 7.

It can be concluded that the Comparative Test at Empa was well designed, planned and executed to provide meaningful and objective results. The fact that the testers involved, both on site and at the laboratories, did not know the identity of the slabs or cores they were testing, guarantees the objectivity of the results obtained.

Although to a varying degree, the Comparative Test proved that there are methods capable of evaluating the "penetrability" of the concrete cover on site, in a reliable and statistically significant manner. In five or six out of seven cases, the test methods were capable of detecting correctly the expected differences in "penetrability" at a significant or highly significant level. Moreover, some of

Table 7 - Performance of the different test methods applied in the Comparative Test

Transport mechanism	Gas-permeability			Water Sorptivity	Electrical Resistivity
Methods Aspect	Autoclam Air	Hong-Parrot	Torrent	Autoclam Sorptivity	Wenner
Significant Discrimination	5/7	5/7	6/7	6/7	5/7
Correlation coefficient R#	0.67	0.92	0.97	0.47	0.83
Measurements per test condition	3	4	6	3	20
Duration per test condition [min]	69	120	99	69	14
Impact: No. holes x diameter [mm]	9 x 6	4 x 20	0	9 x 6	0

with Reference Test for the same transport mechanism

the site methods showed very good correlations with corresponding relevant Reference Test methods.

This opens good perspectives for the application of such methods in practice, for the specification and "in situ" compliance control of the "penetrability" of the vital concrete cover, aiming at performance-oriented criteria regarding the durability of concrete structures.

REFERENCES

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ANNEX A: Details on production and treatment of slabs and drilled specimens

A.1. Casting of slabs and cubes

The 10 batches of concrete to cast the slabs were produced at Empa in batches of 200 to 250 litres (depending on the need to produce reinforced slabs) in a 250 litres pan-type mixer. After a period of dry mixing and after the addition of water and plasticizer, the mixer was operated for 90 seconds.

The whole mixture was transferred into a concrete bucket, then a concrete sample was taken for the determination of the fresh concrete properties as well as the production of four

150 mm cubes.

Four to six 0.3x0.9x0.12 m slabs were cast in steel moulds directly on the vibrating table. Duration of vibration was 20-25 s.

A.2. Concrete properties

Properties of the fresh concrete were determined in accordance with EN 12350:1999. The concrete cubes were demoulded after one day, stored at 20°C and 90% RH until testing at the age of 7 and 28 days. The values reported in Table A1 correspond to the average of two companion cubes.

A.3 Storage

All slabs were demoulded after one day and thereafter stored as shown in Fig. A1. The bottom surfaces of the slabs, as cast, were prepared by marking and numbering four areas (200 x 200 mm) leaving 50 mm distance from the edges of the slab, where the NDT would be applied (Fig. A2).

After the drilling of cores, the slabs from conditions 1 to 6 were placed outdoors under cover, under identical

Fig. A1 - Storage of the slabs according to the test condition.

Table A1 - Test conditions, composition of mixtures and concrete properties										
Test condition	1	7	9	2	6	8	10	3	4	5
w/c	0.40			0.55				0.60	0.40	0.55
Cement type	CEM I 42.5 (OPC)			CEM I 42.5 (OPC)				(OPC)	CEM III B 32.5N (BFSC)	
Mix composition										
Sand 0/4 [kg/m ³]	936	936	936	936	936	936	936	936	936	936
Gravel 4/8 [kg/m ³]	401	401	401	401	401	401	401	401	401	401
Gravel 8/16 [kg/m ³]	573	573	573	573	573	573	573	573	573	573
Cement [kg/m ³]	387	387	387	320	320	320	320	303	380	315
Plasticizer [%]	1.7	1.7	1.7	0.8	0.8	0.5	0.7	0.3	0.9	0.5
Water [kg/m ³]	155	155	155	176	176	176	176	182	152	173
Properties										
Fresh density [kg/m ³]	2357	2365	2374	2354	2327	2342	2327	2288	2371	2334
Temperature [°C]	26.9	26.7	27.0	30.0	27.2	24.8	28.8	28.5	28.2	26.2
Air content [Vol.%]	3.9	3.6	3.3	2.5	3.2	3.0	3.9	4.0	3.1	3.0
Flow table test [mm]	390	410	400	460	420	430	390	490	380	510
Slump [mm]	55	85	80	80	45	50	40	115	95	150
Strength (28 d) [MPa]	62.7	63.6	63.5	48.5	42.7	47.9	42.8	34.4	52.4	38.2

Note: All concretes have the same content of aggregates and the same cement paste volume, only the composition of the latter varies.

Fig. A2 - Disposition of the slabs for NDT, with the 200 x 200 mm test areas marked.

exposition to the environment, to measure carbonation depth at later ages (1 and 2 years).

A.4. Core drilling, specimen preparation and conditioning before testing

After completion of the NDT, four cores per condition were drilled from areas of the slabs that were not affected by the previously applied NDT. All core samples were identified with new codes to avoid any possible association with the NDT already performed on the slabs.

Cores with Ø of 100 mm were cut to a thickness of 50 mm, preserving the original slab surface where the NDT were applied. The resulting discs were dried for 4 days at 50°C in a

ventilated oven. Before and after drying they were weighed and, after drying, were individually wrapped in plastic bags. Then they were safely packed and sent to Portugal by truck. After arriving at LNEC laboratories, the specimens were kept sealed at 20°C till the moment the O₂-Permeability test was started, to be followed in succession by Water Absorption Rate, Electrical Resistivity and Chloride-penetration (ASTM C1202). The non-stationary Chloride "Diffusivity" was determined, based on the colorimetric evaluation of chloride penetration, after the ASTM test was finished.

ANNEX B: Brief description of the NDT applied

B.1 Autoclam Permeability System [6]

The Autoclam system uses a base ring bonded or sealed onto the surface under test, which isolates a test area with a diameter of 75 or 50 mm.

The body of the Autoclam, containing the pressure transducer to record the test pressure, is bolted to the base ring with an O-ring seal during the test (Fig. B1).

In order to carry out an air permeability test, the relative pressure inside the apparatus is increased to slightly above 0.5 bar and the decay in pressure is monitored every minute from 0.5 bar for 15 minutes or until the pressure has diminished to zero. A plot of the natural logarithm of pressure against time is linear.

The result of the test is the Air Permeability Index [$\ln(\text{bar})/\text{min}$], calculated as the slope of the linear regression plot.

Fig. B1 - Sketch of Autoclam Air Permeability test. For Water Sorptivity or Permeability the piston is pushed down to keep the pressure constant.

The Autoclam Permeability system allows the measurement, not only of the air-permeability, but of the water sorptivity and water-permeability as well.

The sorptivity test can be carried out at the same location where the air-permeability was determined, after a waiting period of 1 hour. Water is admitted into the test area through a priming pump with the air escaping through the bleed tube. When the test chamber is completely filled with water the priming pump automatically switches off and the micro pump pressurises the test area to 0.02 bar (0.5 bar for water permeability) above atmospheric, at which stage the test starts. At this pressure the transport of water into capillary pores is considered to be due to absorption rather than by pressure induced flow. As water is absorbed by capillary action, the pressure inside would tend to decrease, hence it is maintained constant by the pump and the control system. The volume of water delivered is measured and recorded every minute for a test duration of 15 minutes, so that the total quantity of water absorbed during the test is accurately known. The plot of the quantity of water absorbed and the square root of time elapsed is linear. The slope of this graph is reported as the sorptivity index with units of $\text{m}^3/\text{min}^{-1/2}$.

Manufacturer's web page: www.amphorandt.com

B.2 Hong-Parrott [7]

It consists in drilling a blind hole 35 mm deep and of 20 mm diameter in the concrete surface (Fig. B2). The sealing of the hole is done with a stainless steel plug fitted with an expanding silicone rubber sealing sleeve. A pressure transducer and a digital indicator are connected to the plug. The cavity is pressurised with air slightly above one atmosphere and the time taken for the relative pressure to drop from 50 to 35 kPa is measured.

The measured time is converted into an apparent permeability K [m^2], as function of the radius affected by the test, as revealed by bubbles in a soap-solution brushed on the concrete surface around the hole.

This method contemplates the measurement of the relative humidity inside the cavity. For that, a relative humidity probe is inserted through the plug and into the cavity without allowing the cavity atmosphere to mix with the ambient air.

Fig. B2 - Sketch of Hong-Parrott Method.

Manufacturer's web page: (Wexham Developments) ourworld.compuserve.com/homepages/wexdev

B.3 Torrent Permeability Tester [8]

The distinctive characteristic features of this method are a two-chamber vacuum cell and a regulator that balances the pressure in the inner (measuring) chamber and in the outer (guard-ring) chamber (Fig. B3).

The cell is placed on the concrete surface and a vacuum is created with the pump in both chambers. Due to the external atmospheric pressure and the rubber rings the cell is pressed against the surface and thus both chambers are sealed, making the cell self-supported. After 1 min stop-cock 1 is closed, which insulates the inner chamber system. From this moment on, the pressure in the inner chamber starts to increase, as air is drawn from the underlying concrete. The rate of pressure rise, which is directly related to the permeability of the concrete, is recorded.

As the vacuum pump continues operating on the outer chamber, through the pressure regulator, the latter ensures that the pressure in the outer chamber is kept always equal to the pressure in the inner chamber. Thus, the outer chamber acts as a "guard-ring", creating a controlled, unidirectional air flow into the inner chamber. That makes it possible to calculate the coefficient of permeability kT [m^2], on the basis of a theoretical model. A correction is applied if the results of the resistivity (measured by the Wenner method) are too low, indicating a moist concrete.

Manufacturer's web page: www.proceq.com

Fig. B3 - Sketch of the Torrent Permeability Tester (TPT).

B.4 Wenner Electrical Resistivity [3]

The electrical resistivity is measured using a probe, consisting of four equally spaced point electrodes that are pressed onto the concrete surface (4-point method), as sketched in Fig. B4. The two outer point electrodes induce the measuring current and the two inner electrodes measure the resulting potential drop in the electric field. The resistance is the ratio of the voltage and the current.

The resistance R [kohm] calculated from the four point measurement is converted into resistivity ρ by:

$$\rho = 2 \cdot \pi \cdot a \cdot R \quad \text{with } a = \text{electrode spacing [cm].}$$

For calibration purposes, the probe is placed with all four electrodes touching a metal sheet of known resistivity.

Fig. B4 - Sketch of Four-Point (Wenner) Method.

ANNEX C: Test results

Table C1 - Results of the Site Tests										
Test Condition	1	2	3	4	5	6	7	8	9	10
Autoclam Air Permeability Index QUB										
mean	0.034	0.032	0.066	0.038	0.056	0.149	0.006	0.034	0.025	0.091
standard deviation	0.009	0.004	0.007	0.013	0.008	0.037	0.001	0.013	0.005	0.020
Parrott K [10^{-16} m^2] LNEC										
mean	0.077	0.128	0.342	0.060	0.159	0.209	0.021	0.050	0.016	0.146
standard deviation	0.062	0.036	0.045	0.024	0.031	0.058	0.011	0.013	0.012	0.035
Torrent kT [10^{-16} m^2] TFB										
mean	0.066	0.297	0.690	0.160	0.208	0.568	0.169	0.252	0.075	0.325
standard deviation	0.009	0.032	0.236	0.040	0.096	0.224	0.038	0.012	0.018	0.122
Autoclam Water Sorptivity Index QUB										
mean	0.961	1.619	1.797	1.815	2.241	3.894	0.085	0.361	0.678	1.765
standard deviation	0.021	0.031	0.235	0.103	0.292	0.158	0.074	0.171	0.005	0.299
Wenner Electrical Resistivity ER [kohm.cm] TNO										
mean	14.2	11.6	13.0	121.9	116.9	13.4	13.2	9.7	19.4	15.9
standard deviation	1.2	0.5	0.6	6.3	7.0	0.9	1.3	0.5	1.5	1.1

Table C2 - Results of the Reference Tests										
Test Condition	1	2	3	4	5	6	7	8	9	10
O ₂ -Permeability kO [10^{-16} m^2] LNEC										
mean	0.0709	0.319	1.257	0.0677	0.186	0.747	0.076	0.314	0.063	0.528
standard deviation	0.0161	0.047	0.173	0.0034	0.032	0.187	0.011	0.021	0.018	
Water Absorption Rate at 24 hours [$\text{kg/m}^2/\text{h}^{1/2}$] LNEC										
mean	0.135	0.341	0.541	0.111	0.229	0.406	0.121	0.334	0.120	0.384
standard deviation	0.007	0.023	0.024	0.011	0.013	0.037	0.004	0.014	0.007	0.014
Electrical Resistivity [kohm.cm] LNEC										
mean	12.5	7.7	6.3	53.7	30.4	8.4	13.1	7.8	15.0	7.6
standard deviation	0.4	0.5	0.8	2.6	3.8	1.1	1.6	1.3	0.6	0.6
ASTM C1202 - Chloride "Penetration" [Coulombs] LNEC										
mean	2237	3316	5033	263	463	4447	2142	5504	2036	5205
standard deviation	33	224	544	7	47	428	71	268	127	933
Chloride "Diffusivity" [$10^{-12} \text{ m}^2/\text{s}$] LNEC										
mean	14.2	33.4	57.1	3.9	5.5	41.2	16.5	43.3	13.9	41.3
standard deviation	2.7	2.4	5.8	1.4	0.7	3.0	2.6	2.9	3.1	3.7

ANNEX D: Practical aspects of Site Tests

Table D1 – Practical aspects		
Autoclam (Air Permeability or Water Sorptivity/Permeability): 3 measurements per test condition		
	Time [min]	Exclusive dedication
Total time to evaluate one test condition	69	24
Average time per measurement	23	8
<p>The instrument, battery-operated, comes in a carrying case, weighing 17.8 kg with accessories. If the ring is bolted, not glued, a hand driller is also needed. Just one operator is required.</p>
<p>Impact on the surface: 9 holes Ø 6mm</p>

Parrott (Air Permeability): 4 Measurements per test condition		
	Time [min]	Exclusive dedication
Total time to evaluate one test condition (excluding waiting time)	120	120
Average time per measurement	30	30
<p>The weight of the equipment, including drilling facilities is about 9 kg. Only the drilling apparatus needs power supply. Just one operator is required.</p>
<p>Impact on the surface: 4 holes Ø 20mm</p>

Torrent Permeability Tester (Air Permeability): 6 measurements per test condition		
	Time [min]	Exclusive dedication
Total time to evaluate one test condition	99	22
Average time per measurement	17	4
<p>The instrument, battery-operated, comes in two carrying cases, weighing 8.6 kg in total. To this, a vacuum pump, weighing ~10 kg should be added, that requires electric power for its operation. Just one operator is required to perform the test.</p>
<p>Impact on the surface: None (picture corresponds to original surface)</p>

TNO Wenner (Electrical Resistivity): 20 measurements per test condition		
	Time [min]	Exclusive dedication
Total time to evaluate one test condition	14	14
Average time per measurement	1	1
<p>The instrument, battery-operated, comes in a carrying case, weighing 1.0 kg in total. Just one operator is required to perform the test.</p>
<p>Impact on the surface: None (picture corresponds to original surface)</p>