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

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

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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.

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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.

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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.

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.

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.

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 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).

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 ($Y=a \cdot X+b$), 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	--	++	++	o	++	++	++
Parrott	o	++	++	++	+	++	++
TPT	++	++	++	o	++	++	++
Water Sorptivity	**Differentiation capability**						
Autoclam Index	++	o	++	+	++	+	++
Electrical Resistivity	**Differentiation capability**						
Wenner	++	--	++	++	--	++	++

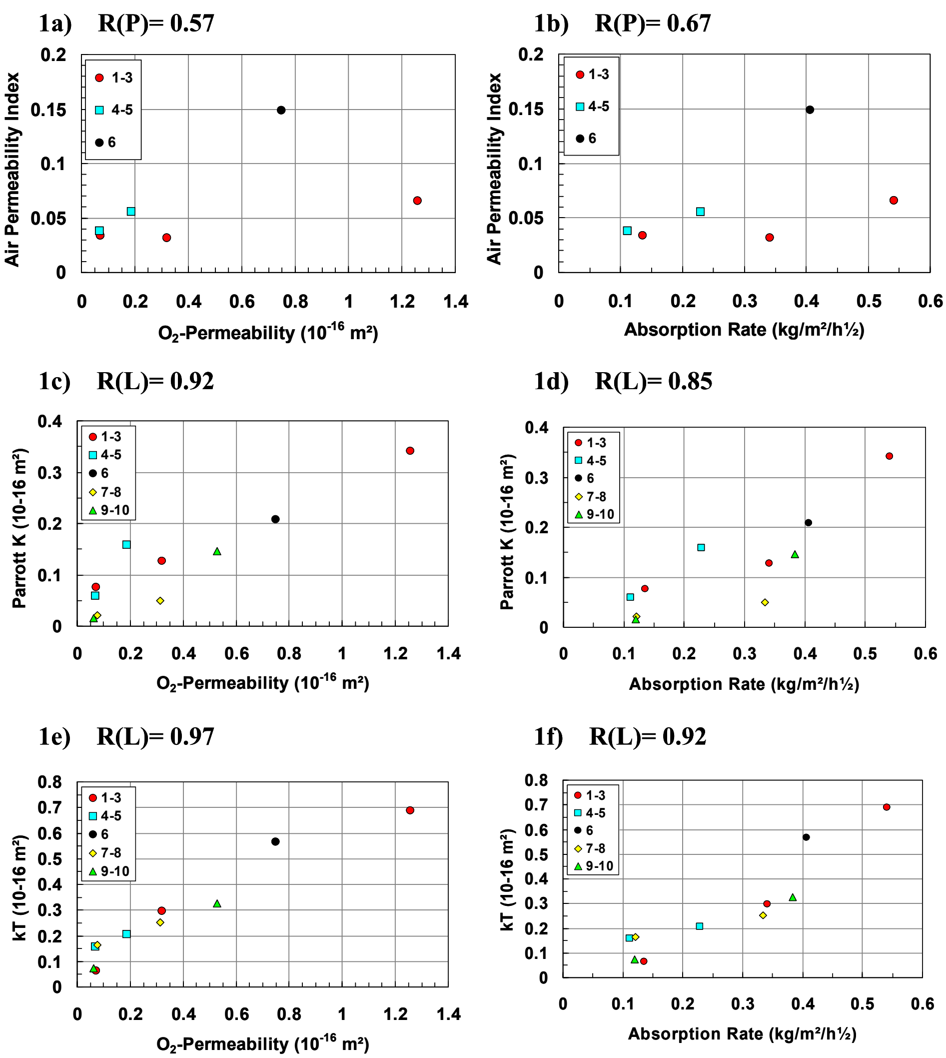

Fig. 1 - Correlation between gas-permeability Site Tests and Reference Tests: 1a) Autoclam-Air vs. O_2-Permeability; 1b) Autoclam-Air vs. Water Absorption Rate; 1c) Parrott vs. O_2-Permeability; 1d) Parrott vs. Water Absorption Rate; 1e) Torrent Permeability vs. O_2-Permeability; 1f) Torrent Permeability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

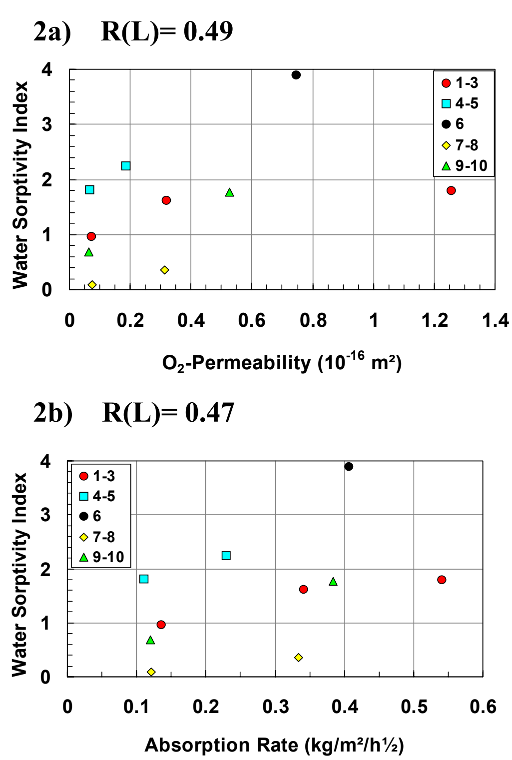

Fig. 2 - Correlation of Water Sorptivity Site Test and Reference Tests: 2a) Water Sorptivity Index vs. O_2-Permeability; 2b) Water Sorptivity Index vs. Water Absorption Rate.

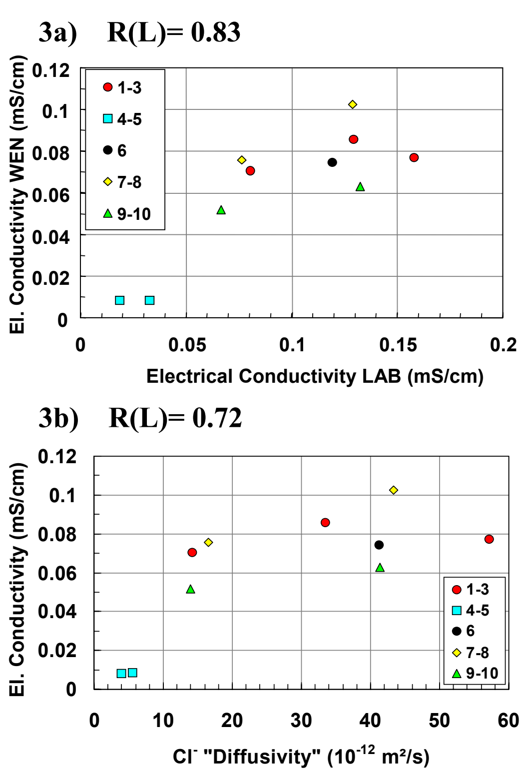

Fig. 3 - Correlation between Electrical Resistivity (Wenner) Site Test and Reference Tests: 3a) Electrical Conductivity (Wenner) vs. Electrical Conductivity (LAB); 3b) Electrical Conductivity (Wenner) vs. Chloride "Diffusivity".

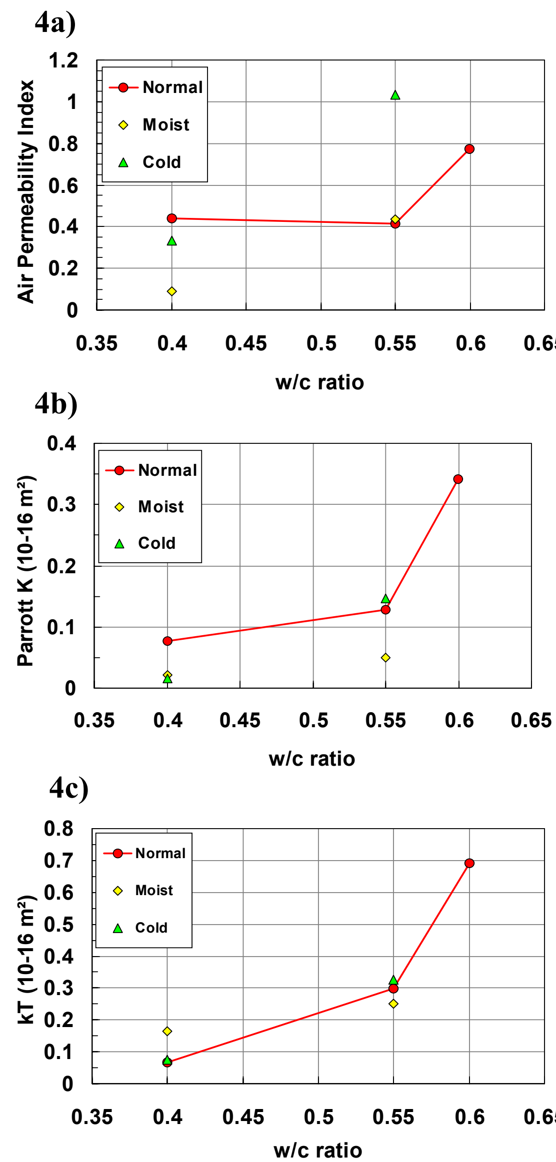

Fig. 4 - Effect of moisture and ambient temperature on the Gas-Permeability Site Tests: 4a) Autoclam-Air Permeability Index; 4b) Parrot K; 4c) Torrent Permeability kT.

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

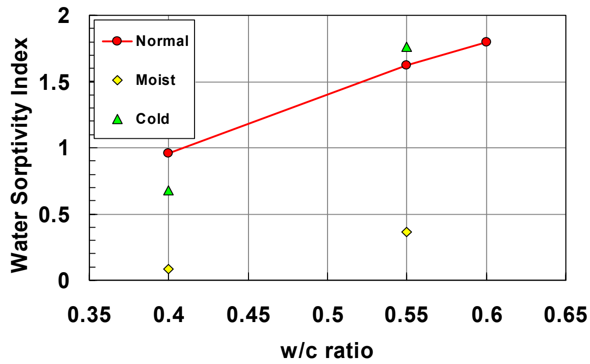

Fig. 5 - Effect of moisture and ambient temperature on Autoclam Water Sorptivity Index.

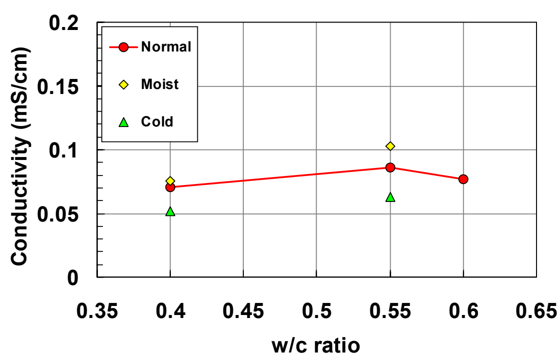

Fig. 6 - Effect of moisture and ambient temperature on Electrical Conductivity (Wenner).

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.

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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

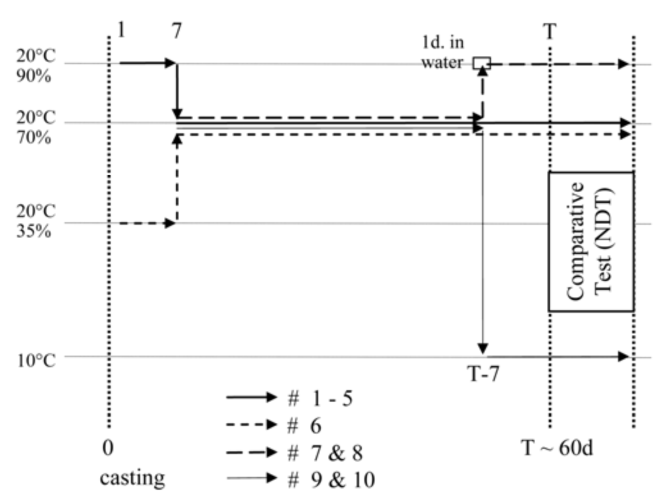


Fig. A1 - Storage of the slabs according to the test condition.

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/m³]	936	936	936	936	936	936	936	936	936	936
Gravel 4/8 [kg/m³]	401	401	401	401	401	401	401	401	401	401
Gravel 8/16 [kg/m³]	573	573	573	573	573	573	573	573	573	573
Cement [kg/m³]	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/m³]	155	155	155	176	176	176	176	182	152	173
Properties										
Fresh density [kg/m³]	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 O_2-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(bar)/min], calculated as the slope of the linear regression plot.

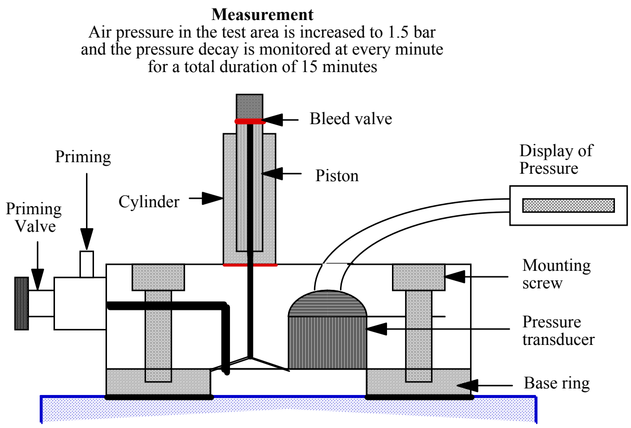


Fig. B1 - Sketch of Autoclam Air Permeability test. For Water Sorptivity or Permeability the piston is pushed down to keep the pressure constant.

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 $m^3/min^{-1/2}$.

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 [m²], 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.

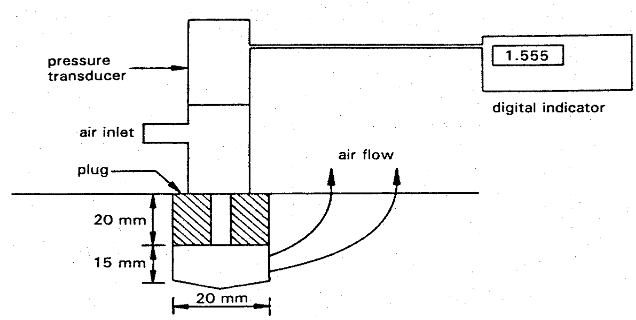


Fig. B2 - Sketch of Hong-Parrott Method.

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 [m²], 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

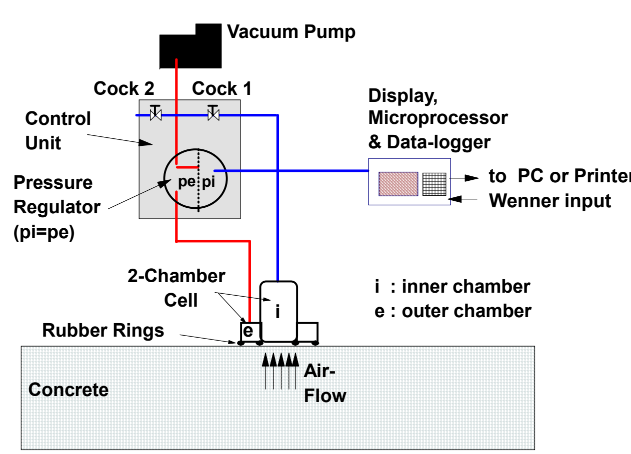


Fig. B3 - Sketch of the Torrent Permeability Tester (TPT).

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:

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

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

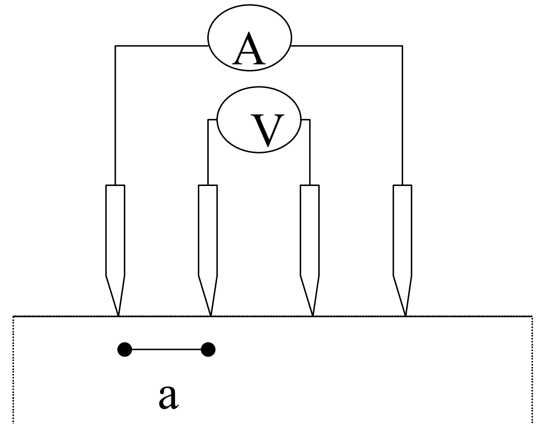


Fig. B4 - Sketch of Four-Point (Wenner) Method.

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 [$kg/m^2/h^{1/2}$] 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} m^2/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

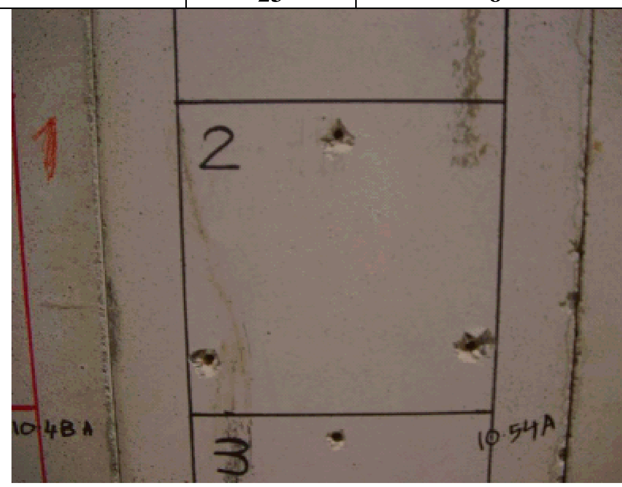
ANNEX D: Practical aspects of Site Tests

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**

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.

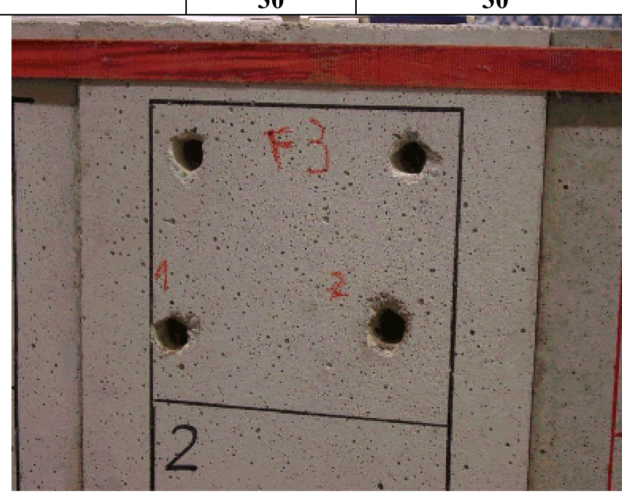


Impact on the surface: 9 holes Ø 6mm

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**

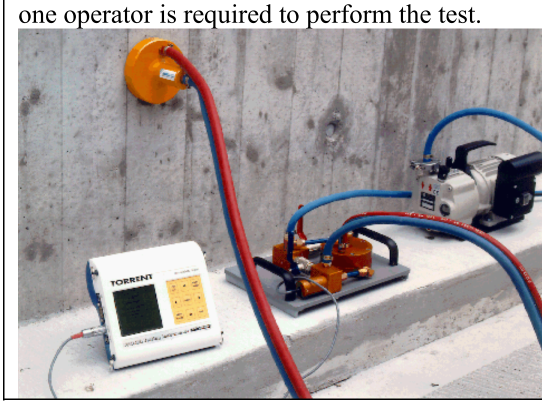
The weight of the equipment, including drilling facilities is about 9 kg. Only the drilling apparatus needs power supply. Just one operator is required.



Impact on the surface: 4 holes Ø 20mm

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**

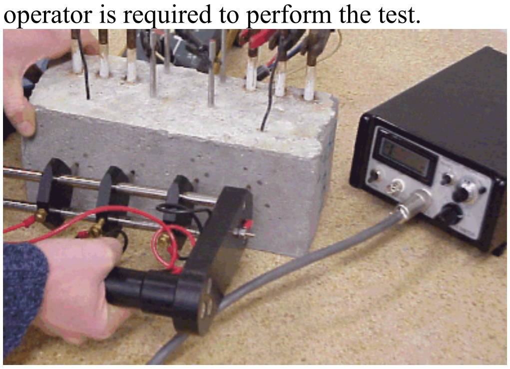
The instrument, battery-operated, comes in two carrying cases, weighing 8.6 kg in total. To this, a vacuum pump, weighing ~10 kg should be added, that requires electric power for its operation. Just one operator is required to perform the test.



Impact on the surface: None
(picture corresponds to original surface)

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**

The instrument, battery-operated, comes in a carrying case, weighing 1.0 kg in total. Just one operator is required to perform the test.



Impact on the surface: None
(picture corresponds to original surface)

UPDATE of article RILEM TC 189-NEC "Comparative test - Part I - Comparative test of penetrability methods", Materials & Structures, v38, Dec 2005, pp. 895 - 906.

R. Torrent, Chairman of TC 189-NEC
10 October 2007

1. <u>Object of this Update</u>

The original article presented a summary of the results and conclusions of a Comparative Test conducted within the scope of RILEM TC 189-NEC "Non destructive Evaluation of the Concrete Cover". The Comparative Test (CT) was intended to assess, under the same conditions, the performance of different non-destructive test (NDT) methods designed to measure the "penetrability" of the concrete cover on site.

The original article reflects accurately the situation at the date of publication.

In view of concerns expressed by one of the participants on the effect of the moisture content of the concrete, at the time of the tests, on the results obtained from one of the NDT methods, namely the Autoclam Permeability System, the analysis of the results was revised.

The aim of the present article is to update the results, presented in the original article, as a consequence of this revision.

For a full understanding of the present update, a reading in conjunction with the original article is recommended.

Alternatively, the reader is referred to Chapter 8 of RILEM Report 40: State-of-the-Art Report on Non-Destructive Evaluation of the Penetrability and Thickness of the Concrete Cover, by RILEM Technical Committee 189-NEC, (ISBN 978-2-35158-054-7), Eds. R. Torrent and L. Fernández Luco (2007) RILEM Publications S.A.R.L. That Chapter contains the full final report of the Comparative Test Part I - Comparative test of penetrability methods, including all recorded data.

2. <u>Curing and Pre-conditioning of the Slabs</u>

All slabs were initially stored in a moist room (20°C, 90% RH) for 24 hours. Subsequently they were demoulded and treated as detailed below.

- Sets 1 to 5 were kept in the moist room (20°C, 90% RH) until 7 days of age. Thereafter, the specimens were stored in a room at "Normal" ambient conditions (20°C, 70% RH) until testing.
- Set 6 was stored in a dry room (20°C, 35% RH) until 7 days of age. Thereafter, the specimens were kept in a room at "Normal" ambient conditions (20°C, 70% RH) until testing.
- The treatment of Sets 7 and 8 initially followed the same cycle as Sets 1 to 5. However, 7 days prior to commencement of the NDT tests the samples were immersed in water for 1 day and thereafter kept in a "Moist" room (20°C, 90% RH) until testing. Testing samples that were treated in this way simulated measurements carried out after rainfall in an environment of high relative humidity.
- The treatment of Sets 9 and 10 initially followed the same cycle as Sets 1 to 5. However, for a period of 7 days prior to commencement of the NDT tests (and during the tests) the samples were kept in a "Cold" room (10°C, RH not controlled). Testing samples that were treated in this way simulated measurements carried out in an environment of low ambient temperature.

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

3. Conditions of the slabs when tested with NDT

In the planning of the experiment, a specific treatment of the slabs was agreed and rigorously observed. There was no target for the internal RH (i.e. moisture condition) of the slabs, so the resulting RH was a consequence of the agreed treatment. As a result of the different treatments, the concretes presented varying conditions of temperature and moisture at the time when the various "penetrability" tests were applied.

To have an indication of the temperature and moisture conditions of the concrete in the slabs for the different Test Conditions (at the date of the CT), measurements of Temperature and Relative Humidity were performed, both by LNEC (Portugal) and Queen's University Belfast (QUB, UK), inside drilled holes sealed to create a cavity, (35 and 10 mm deep, respectively). Table U.1 presents the results obtained.

Table U.1 - Temperature and Relative Humidity Measured in the Slabs

Test Condition	Room Conditions	T [°C] of Slab (QUB)	RH [%] of Slab (QUB)	T [°C] of Slab (LNEC)	RH [%] of Slab (LNEC)
1	"Normal" T = 20 °C RH = 70 %	19.2	78.0	20.1	82.1
2		---	---	20.3	83.8
3		---	---	19.9	84.3
4		---	---	20.0	84.0
5		---	---	20.3	85.1
6		---	---	20.1	82.5
7	"Moist" T = 20 °C RH = 90 %	19.5	90.3	19.8	90.6
8		19.6	89.5	19.9	92.1
9	"Cold" T = 10 °C	10.0	89.1	11.0	82.5
10		9.9	87.3	11.1	86.5

As explained above, the planning of the experiment aimed at achieving special testing conditions for Sets 7 and 8 ("Moist") and for Sets 9 and 10 ("Cold").

From Table U.1 it is possible to confirm that the "Moist" and "Cold" conditions were actually achieved. Indeed, for Sets 7 and 8 the relative humidity measured in the concrete ranged between 90 and 92% (the temperature was close to 20°C). Similarly, for Sets 9 and 10, the temperature measured in the concrete was 10-11°C (the relative humidity ranged between 82 and 89%).

For Sets 1 to 6, tested under "Normal" conditions, the relative humidity of the concretes was within the range 78 to 85% and the temperature was close to 20°C.

As a result of these measurements, Table 1 of the original article should be replaced by Table U.2 (the main change being in the definition of the condition for sets 1 to 6, referred now as "Normal" instead of "Dry", as presented in the original article).

Table U.2 - Test Conditions Investigated in the Experiment

	Test Condition									
Variable	**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	OPC	OPC	BFSC	BFSC	OPC	OPC	OPC	OPC	OPC
Moist Curing (days)	7	7	7	7	7	1	7	7	7	7
Condition when NDT applied	"Normal"						"Moist"		"Cold"	

4. Effect of the moisture conditions on the performance of the Autoclam Permeability System

As shown in Table U.1, almost invariably the relative humidity of the slabs exceeded 80%, even for those stored for almost 2 months under "Normal" ambient conditions (20°C, 70% RH). This put all NDT methods based on gas transport or water suction under rather challenging conditions.

In the particular case of the Autoclam Permeability System, it is important to highlight that its Operating Manual states "…it is recommended that tests are carried out when the concrete is relatively dry (i.e. when the internal relative humidity of the cover concrete up to a depth of 10mm is less than 80%)."

Therefore, the results obtained in the CT with the Autoclam instrument must be taken with caution as they might have been affected by the fact that the RH of the concretes was almost invariably above 80%.

5. Correlation to Reference Tests

With the above limitation in mind, the performance of the Autoclam test was revised, in particular the correlation of its results with Reference laboratory tests involving the same or similar "penetration" mechanism.

In the original article, on request of the participant who applied the Autoclam Permeability System, it was agreed that the correlations were made omitting for the calculation the test data corresponding to Sets 7 to 10, as they were clearly made on concretes with high RH (Figs 1a and 1b of the original article).

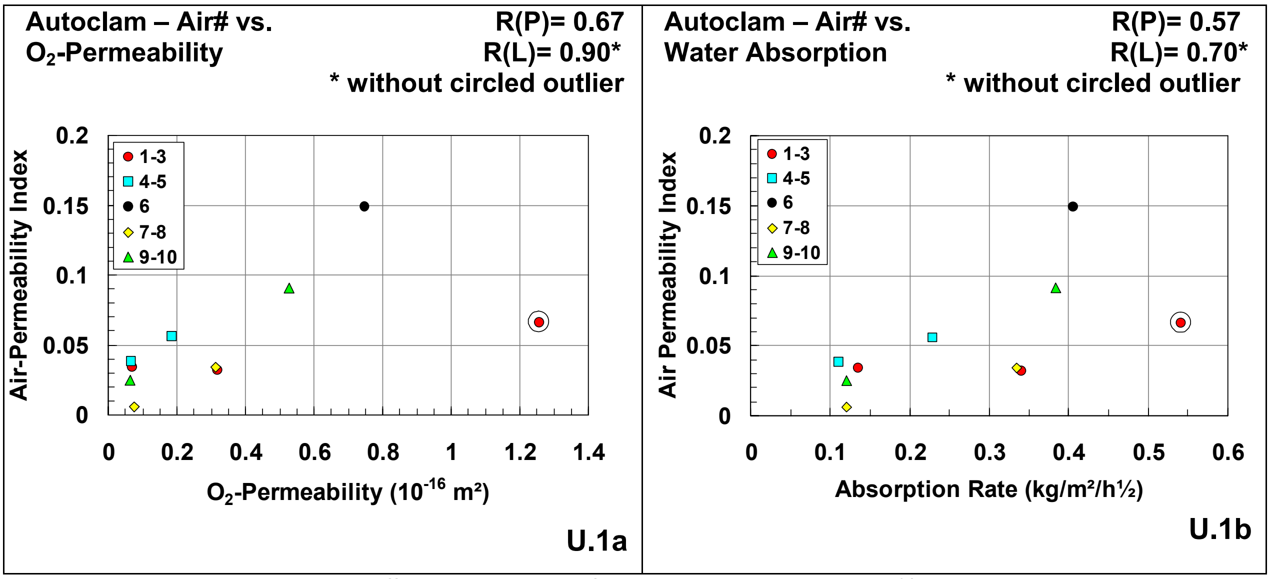
A further revision of the data, including all sets 1 to 10, revealed that the result corresponding to Set 3 falls completely out of the reasonable general trend of the results of the other 9 Sets.

Based on that, the correlations have been recalculated with the 10 results and also without the "outlier" result of Set 3.

The graphical regressions for the Autoclam Air Permeability Index, together with the correlation coefficients R, are presented in Figs. U.1a and U.1b (the outlier result is marked with a circle). Therefore, Figs. U.1a and U.1b should replace Figs. 1a and 1b of the original article, respectively.

As a consequence, the second paragraph of Section 5.2.1 of the original article (starting with "...Regarding correlation with the Reference Tests... ") should be replaced by the following one:

"Regarding correlation with the reference tests, we can say that all three methods present excellent correlations with the RILEM-Cembureau O2-Permeability and also (albeit to a lesser extent) with the Water Absorption Reference Tests. An outlier was apparent in the results of Autoclam, indicating a possible underestimation of the permeability of the concrete with w/c= 0.60 (Test Condition 3), compared to the value obtained with the RILEM-Cembureau method. When this result is disregarded, the correlation coefficients are significantly improved."

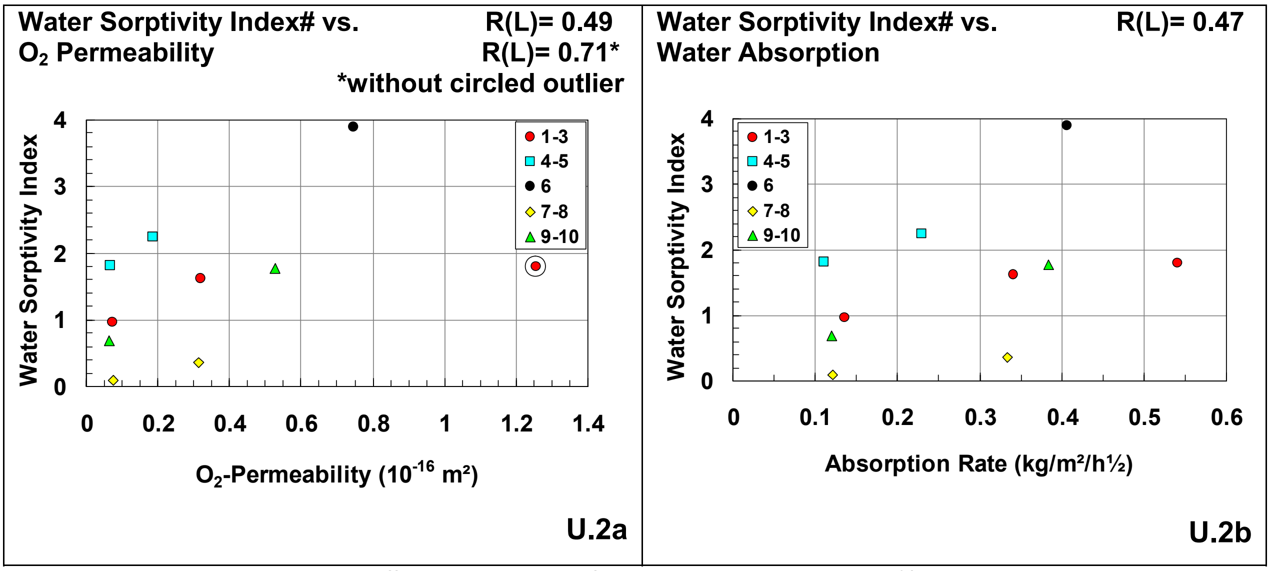


These results might have been affected by the RH of the concretes exceeding 80%, maximum recommended for performing the Autoclam Test

Fig. U.1 - Correlation between Air Permeability Index and related Reference Tests

A similar revision was conducted for the results of the Autoclam Water Sorptivity Index, with the results shown in Figs. U.2a and U.2b. Figure U.2a should then replace Fig. 2a of the original article.

Regarding Fig. U2b (identical to original Fig. 2b), the result for Set 3 does not depart from the general trend, hence the reason why only one correlation coefficient is reported, as in the original article.



These results might have been affected by the RH of the concretes exceeding 80%, maximum recommended for performing the Autoclam Test

Fig. U.2 - Correlation between Water Sorptivity Index and related Reference Tests

6. Conclusions of the Comparative Test

The conclusions presented in Section 6 of the original article are repeated below; they remain identical with the exception that Table U.3 should replace the original Table 7.

“A summary of the quantitative recorded aspects of the performance of the test methods is presented in Table U.3.

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 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.”

Table U.3 - Performance of the different NDT methods applied in the Comparative Test

Transport mechanism	Gas Permeability			Water Sorptivity	Electrical Resistivity
Methods / Aspect	Autoclam Air	Hong-Parrot	Torrent	Autoclam Sorptivity	Wenner
Discrimination *	□□□□□■■	□□□□□□■	□□□□□□■	□□□□□□■	□□□□□■■
Correlation Coefficient R #	0.67 0.90 @	0.92	0.97	0.47	0.83
Measurements per Test Condition	3	4	6	3	20
Duration per Test Condition (minutes)	69	120	99	69	14
Impact: No. holes x diameter	9 x 6 mm	4 x 20 mm	0	9 x 6 mm	0

* □ = Significant or Highly Significant ■ = Not Significant or Wrong
# with Reference Test for the same transport mechanism
@ without “outlier” result for Test Condition No. 3