Site Air-Permeability of HPSFR and Conventional Concretes

Roberto Torrent, Marco di Prisco, Verónica Bueno and Fabio Sibaud

Synopsis: An investigation in an industrial building devoted to manufacturing equipment for the pharmaceutical industry was carried out. Stringent requirements were set for the building, in particular a very low permeability was required against the relatively high water-table. The design of the building, as well as the quality of the concrete, was concerned with providing an impermeable barrier, besides structural safety and functionality.

Different concrete qualities were used for different parts of the building. The most critical areas were built with steel fiber reinforced concrete (SFRC), both precast and cast *in situ*. In particular, some slabs were cast *in situ* with self-compacting (SCC-SFRC). Concrete samples were cast on site and taken to the laboratory for testing mechanical and durability performance. In order to verify the degree of impermeability reached in the end product, on site air-permeability measurements were conducted on representative elements of the structure. The paper presents and analyzes the air-permeability results obtained on several different elements, concluding that the cast on site SCC-SFRC presents a unique extremely low permeability and that the external wall tested has an air-permeability low enough to withstand the environment to which it is exposed. On the contrary, some non-critical internal elements, both cast on site and precast, present rather high and scattered air-permeability values.

Keywords: air-permeability, durability, fiber-reinforced concrete, site testing, water-tightness

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INTRODUCTION

This work refers to an industrial building meant for a company devoted to manufacturing equipment for the pharmaceutical industry. It is a two-storey building, as illustrated in Fig. 1, located in the city of Como, Italy.

Stringent requirements were set for the building; in particular a very low permeability was required against the relatively high water-table. The design of the building, as well as the quality of the concrete, was concerned with providing an impermeable foundation barrier, besides structural safety, durability and functionality.

Different concrete qualities were used for different parts of the building. The most critical areas were built with steel fiber reinforced concrete (SFRC) cast *in situ*. Some slabs were cast with self-compacting SFRC (SCC-SFRC).

To verify the degree of impermeability reached in the end-product, on site air-permeability measurements were carried out on representative elements of the structure.

The main objective of the investigation was to measure – on site - the air-permeability of the SFRC foundation beams and slabs, responsible of transferring loads to the ground and providing water-tightness to the building. Given the wide range of concretes used in the construction, some other elements were also tested for comparative purposes. In particular, extensive tests were made on an external wall, exposed to the environment, to check its expected durability performance. In some cases, parallel tests were conducted on laboratory specimens used for structural characterization and quality control of the concretes.

STRUCTURAL ELEMENTS INVESTIGATED

Table 1 describes the main elements tested for air-permeability and their structural function. Figs. 2 and 5 show pictures of the elements tested.

CONCRETE MIX DESIGNS AND MAIN CHARACTERISTICS

Proportions of the Mixes

Table 2 presents the final design of the mixes used for the construction of the different elements of the structure. These mix designs were arrived at after different trials, both in the laboratory and in pilot placements on site.

Materials Used

The cement used for the construction of the building is CEM IV/A 42.5R LH, according to the classification of European Standard EN 197-1 [1]; it is a pozzolanic cement, containing between 11 and 35% of pozzolan, classified as low heat of hydration, with a rapid development of a moderate strength. Only precast columns were made of OPC cement Type CEM I 52.5 R.

The aggregates used for mixes E and G are declared in Table 2 and were separated into three fractions: 0-4 mm, 0-8 mm, 4-16 mm: the grading curves are reported in Fig. 6. The other two mixes 8-14 mm and 11-22 mm declared for the mix P are known only in the proportions.

Several chemical admixtures were introduced into the mixes. In the SCC-SFRC, DYNAMON SR41 (a superplasticizer-retarder) and MAPECURE E (shrinkage reducer), both manufactured by MAPEI, were used. In the concrete without fibers, Sikaplast 90 and SIKA Plastiment VZ were used, both to increase the workability and the related setting time.

Hooked-end steel fibers, commercially known as Dramix 4D 65/60BG, manufactured by Bekaert, were used in the SFRC mixes. They are 60.5 mm (2.4 in) long and 0.9 mm (0.035 in) in diameter, i.e. with an aspect ratio 65, with yield strength f_{yk}= 1600 MPa (229 ksi).

Powdered Limestone filler was added into mix G to optimize the mix design in terms of strength level, flowability and cost.

Mechanical Properties of the Concretes

The mix designs of mix E and G were made to provide adequate self-compacting workability to the SFRC, checked by tests in the laboratory (L-box) and in pilot placements on site. The SFRC mixes had to comply with the requirements corresponding to SFRC Class 3c of the Model Code 2010 [2], that specifies residual stresses of $f_{R1,k}$ = 3.0 MPa (429 psi) and $f_{R3,k}$ = 2.7 MPa (386 psi), for crack mouth opening displacement CMOD of 0.5 mm (0.02 in) and 2.5 mm (0.1 in), respectively. These values, as well as the flexural tensile strength (Limit Of Proportionality) $f^{f}_{ct,L,}$, were obtained from 3-point bending tests on notched beams, according to European Standard EN 14651 [3]. The mechanical properties measured on concretes with the different mix designs are reported in the lower part of Table 2.

SITE AIR-PERMEABILITY EXPERIMENTAL INVESTIGATION

Air-permeability tests were performed on site, on the as-cast concrete surface condition, following the prescriptions of Swiss Standard SIA 261/1:2013, Annex E "Air-Permeability on the Structure" [4].

The test applied is the non-destructive "double-chamber vacuum cell" method, in which the rate of pressure rise in the previously evacuated inner chamber is recorded, which relates to the permeability of the underlying concrete. The pressure in the inner and outer (guard-ring) chamber is kept balanced by means of a regulator, resulting in a unidirectional flow into the inner chamber. Under these conditions, a model allows calculating the coefficient of air-permeability kT of the surface concrete layers affected by the test. kT is expressed in m^2 (1 m^2 = 10.76 ft^2). For more details, the reader can refer to [5].

Two instruments were used for the tests, namely a 3rd generation instrument *PermeaTORR* (Fig. 3) and a 4th generation instrument, *PermeaTORR AC* (Active Cell), see Fig. 5. On some spots, showing well differentiated kT values, the coefficient of air-permeability kT was measured with both instruments, obtaining quite similar results, as shown in Fig. 7, confirming what has been reported in [6].

As stipulated in [4], prior to testing the air-permeability, the surface moisture of the concrete was measured with an electrical impedance instrument (CMEX II), to check that the indication was not above 5.5%, which was the case for all tests.

Moreover, kT tests were performed on cast specimens used for material characterization and quality control. The results of the site tests are shown on the left-hand side of Table 3, whilst those obtained on laboratory specimens are shown on the right-hand side of the Table. Since kT follows a log-normal distribution (Annex D of [7,8]), the central value reported is the geometric mean of the measured values (mean of the logarithms) and for the scatter is the standard deviation of the $\log_{10}$ of the values (sLOG).

ANALYSIS OF THE RESULTS

To facilitate their analysis, the results presented in Table 3 are plotted in graphical form in Fig. 8. The dot represents the value of kTgm and the equal segments at each side of the dot represent ± sLOG (on a logarithmic scale x-axis).

At the top of the chart the classification of permeability, based on kT, is shown. Comparative tests have shown that the classification matches well that of ASTM C1202, based on electric charge passed (Coulombs) [9] which, incidentally, is not a suitable test to assess the 'permeability' of SFRC due to the conductive steel fibers. In addition, a short vertical segment at kT = $2.0\ 10^{-16}$ m² is drawn, the meaning of which will be explained later.

What is immediately obvious in Fig. 8 is the wide range of kT values obtained on the different concretes tested. Indeed, the values of kT recorded "in situ" on the different elements span 4 orders of magnitude, from "Very Low" to "High" permeability classes.

SCC-SFRC Elements

The better permeability performance of the SCC-SFRC foundation elements (FB, FS1, FS2), compared with the RC elements (including the cast-on-site walls and the precast columns) is evident in Fig. 8. This can be attributed to a mix design with low w/c ratio, to the inclusion of a shrinkage-reducing admixture and, furthermore, to the positive contribution of steel fibers in preventing shrinkage cracking.

Looking at the kT values of SCC-SFRC in more detail, it results that the foundation slabs on the ground (FS1 and FS2) present lower permeability than the foundation beams and even than the laboratory specimens (flexural beams). The foundation beam was made with mix E, while the two foundation slabs were made of the same nominally identical mix G which is favoured by filler addition. Moreover, this better performance may lie on the fact that the ground slabs were kept ponded with water for several weeks after casting, thus receiving a better curing than the other elements/specimens.

The kTgm value recorded for foundation slab FS1, $0.0045\ 10^{-16}$ m², is the lowest ever recorded by the authors on site concrete. Compare it with values, recorded on precast elements made with concretes meant to last over 100 years in a marine environment, of $0.027\ 10^{-16}$ m² in the Port of Miami Tunnel [10] and of $0.069\ 10^{-16}$ m² in the Hong-Kong-Zhuhai-Macao Link [11]. These reported data match well the values obtained for SCC-SFRC in elements FS2 and FB. This High Performance, coupled with the self-compacting performance, indicates that the SFRC concrete cast on site in this building can be classified as a HP-SFRC.

It is worth noticing that the kTgm values measured on the foundation slabs on the ground (0.023 and $0.0045\ 10^{-16}$ m²) are much lower than that obtained on the laboratory flexural beams, made with the same concrete mix ($0.103\ 10^{-16}$ m²). This is a rather unusual case as, in general, laboratory specimens show lower kT values than the corresponding site concrete, due to the better compaction and curing conditions applied to the specimens [12, 13]. The inversion of this general rule can be found on the exceptional conditions under which the foundation slabs were built: self-compacting workability and several weeks of curing by ponding; this confirms the importance of good concreting practices on the performance of the end products.

External Wall

The case of the external wall merits some analysis. The external face of the building walls will be directly exposed to the environment. The city of Como has a Mediterranean climate, quite rainy (around 1300 mm/year or ~50 in/year) and with temperatures occasionally dropping below 0°C (32°F) in winter. It can be classified as XC4 (severe carbonation risk) and XF1 (mild frost risk), according to EN 206. For ACI 318, that would correspond to exposure classes C1 and F1.

For climates XC4 and XF1, Swiss Standard SIA 262/1:2013 [4] specifies a "statistical upper limit" of the air-permeability kTs = $2.0\ 10^{-16}$ m². It is worth mentioning that the building in question lies less than 10 km of the Italian/Swiss border, where the requirements of [4] apply.

The compliance criterion of SIA 262/1:2013 [4] states that not more than 1 result out of 6 may exceed the specified value kTs ($2.0\ 10^{-16}$ m² for this exposure case) and that, if just 2 results exceed kTs, another 6 tests should be conducted, out of which, again, not more than 1 may exceed kTs. Fig. 9 shows the O-C curve for that conformity criterion, showing in abscissae the proportion of the lot having a permeability kT higher than kTs and in ordinates, the probability of accepting such a lot, applying the Swiss conformity criterion [7,9].

The intensive 31 test results obtained on the external wall EW showed a kTgm = 0.21 and a sLOG = 0.82 (Table 4); a simple calculation, assuming that log(kT) is normally distributed, indicates that the proportion of the wall with kT > 2.0 10^{-16} m² is just 12%. The O-C curve of Fig. 9 yields a probability of acceptance of such lot of 95%, which is a satisfactory result.

Just as a speculation, if internal walls IW1 and IW2 had been external, i.e. exposed to the same environment as wall EW, their probability of acceptance would have been the marginally acceptable level of 60% and the unacceptably low level of 20%, respectively.

Internal Columns

The values obtained on the precast columns are rather disappointing. They show a high kTgm and a high scatter. A closer look to the surface of the elements showed a crazed skin, which may have affected the air-permeability measurements. However, on one spot, the removal of the skin revealed a visible crack on the concrete underneath; given that these internal elements play no role in terms of water-tightness or durability of the structure, the matter was not pursued further.

CONCLUSIONS

Based on the results of this experimental investigation, the following conclusions can be drawn:

1. The tests conducted on site showed a wide range of air-permeability values for the different elements investigated, reflecting the different mix designs and concreting processes involved.
2. The self-compacting, steel-fiber reinforced foundation concretes showed permeabilities in the range of “Low” and “Very Low” classes, suitable for their function as water-tight barrier against the high water-table level underneath. Based on their high performance, they can be classified as HP-SFRC.
3. To the knowledge of the authors, foundation slab FS1 showed record-low kT values for site concrete.
4. Foundation slabs FS1 and FS2 even yielded lower site kT values than laboratory samples made with the same mix, a rare example to be attributed to their self-compacting workability and long term curing by water ponding.
5. The intensively tested external wall, exposed to an environment that can be classified as XC4, XF1 (EN 206) or C1, F1 (ACI 318), showed results of kT in compliance with the upper limit kTs = 2.0 10^{-16} m², specified in Standard SIA 262/1:2013 of neighboring Switzerland.
6. The internal cast-on-site walls and precast columns showed “Moderate” to “High” air-permeability values, that are rather disappointing, but have no consequences on the serviceability and durability of the structure, given their indoors location.

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TABLES AND FIGURES

Table 1–Characteristics of the elements tested for site air-permeability

Code	Function	Concrete Type	Mix Design	Cast	Age at Test (d)
FB	Foundation Beam	SCC-SFRC	E	on site	163
FS1	Foundation Slab	SCC-SFRC	G	on site	86
FS2	Foundation Slab	SCC-SFRC	G	on site	82
SS	Suspended Slab 1st Floor	RC	S	on site	144
EW	External Wall	RC	P	on site	175
IW1,2	Internal Walls	RC	P	on site	176
PP1-3	Internal Precast Columns	RC	Columns	plant	n.a.

SCC=Self-consolidating concrete; SFRC= Steel-fiber reinforced concrete; RC= Reinforced concrete

Table 2–Composition and mechanical properties of the concrete mixes used in the investigated elements

Component or Property	Mix E	Mix G	Mix S (proprietary)	Mix P	Columns (proprietary)
Cement (kg/m^3) / *(lb/yd^3)*	470 / *792*	380 / *641*		360 / *607*	480 / *808*
Limestone Filler (kg/m^3) *(lb/yd^3)*	-	100 / *169*		-	-
Water (kg/m^3) *(lb/yd^3)*	188 / *317*	165 / *278*		180 / *234*	180 / *252*
Superplasticizer (% cement wt.)	1.62	1.58		1.2	3.00
Shrinkage Reducer (% cement wt.)	0.85	1.44		-	-
Sand 0/4 mm (kg/m^3) *(lb/yd^3)*	1008 / *1700*	509 / *858*		361 / *608*	-
Gravel 0/8 mm (kg/m^3) *(lb/yd^3)*	504 / *850*	763 / *1286*		721 / *1214*	-
Gravel 4/16 mm (kg/m^3) *(lb/yd^3)*	171 / *288*	424 / *715*		-	-
Gravel 8/14 mm (kg/m^3) *(lb/yd^3)*	-	-		198 / *333*	-
Gravel 11/22 mm (kg/m^3) *(lb/yd^3)*	-	-		523 / *881*	-
Steel Fibres (kg/m^3) *(lb/yd^3)*	35 / *59*	35 / *59*		-	-
w/c ratio	0.40	0.43		0.38	0.46
$R_{cm,\,cube}$ @ 28 d (MPa)/(*ksi*)		59.3 / *8.6*		35/5.1	67/9.7
$f^{f}_{ct,L}$ @ 28 d (MPa)/(*psi*)*	4.06 / *589*	2.69 / 390		-	-
$f_{R1,k}$ @ 28 d (MPa)/(*psi*)*	3.91 / *567*	5.32 / 772		-	-
$f_{R3,k}$ @ 28 d (MPa)/(*psi*)*	3.86 / *560*	4.06 / 589		-	-
Model Code SFRC Class	3d	5b		-	-

* assuming LogNormal distribution on test results of 12 beams, obtained at 35-60 days of age

Table 3–Statistical parameters of air-permeability test results obtained on site and in the laboratory

Site Tests			
Element	No. of Tests	kTgm 10^{-16} m^2	sLOG
FB	7	0.058	0.71
FS1	6	0.023	0.22
FS2	6	0.0045	0.27
SS	12	0.123	0.64
EW	31	0.210	0.82
IW1	12	0.389	1.23
IW2	12	1.513	0.92
PP1	8	0.725	1.06
PP2	8	0.629	0.57
PP3	8	2.103	0.81

1 m^2 = 10.76 ft^2

Laboratory Tests			
Specimen	No. of Tests	kTgm 10^{-16} m^2	sLOG
Cubes 150mm /*5.9 in*	11	0.330	0.57
Notched Beams*	13	0.103	0.34

*L: 1500/*59.1;* H: 500/*19.7;* W:300/*11.8* (mm/*in*)

Fig. 1–Overview of the building during advanced construction stage

Fig. 2 – View of external wall and suspended slab (behind parapet)

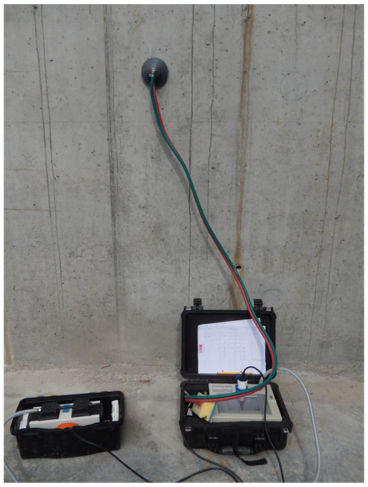

Fig. 3 – kT test on Internal Wall 2

Fig. 4 – View of Internal Wall 1, Foundation Slabs 1 and 2 and Foundation Beam

Fig. 5 – kT test on Foundation Beam

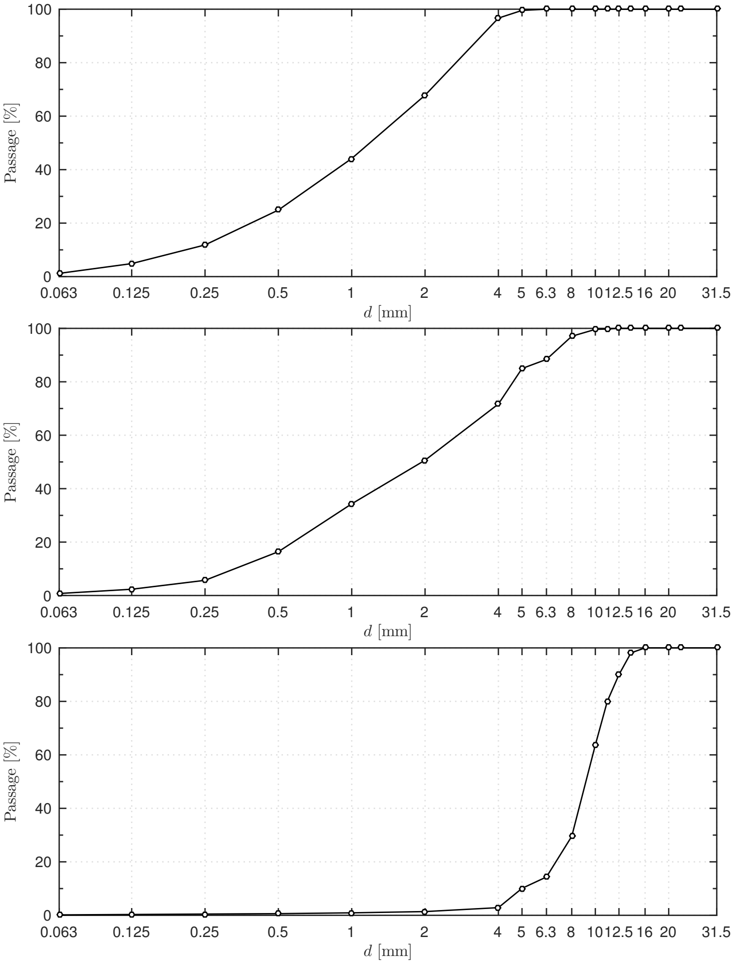

Fig. 6 – Grading curves of the aggregate fractions used in mixes E and G.

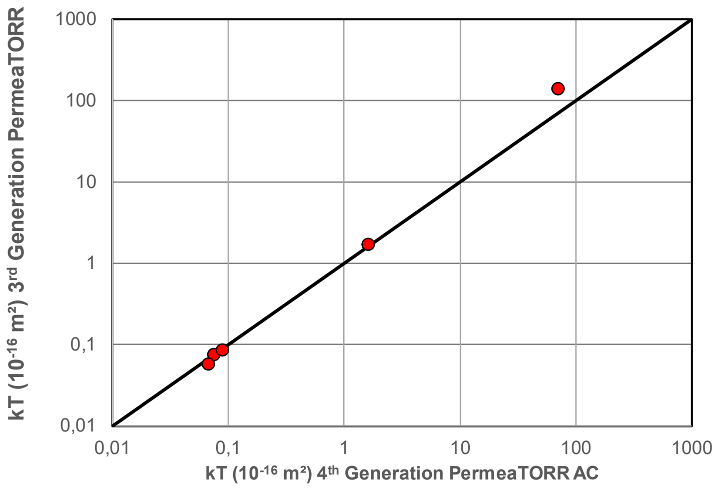

Fig. 7 – Comparison of air-permeability kT, measured with both instruments

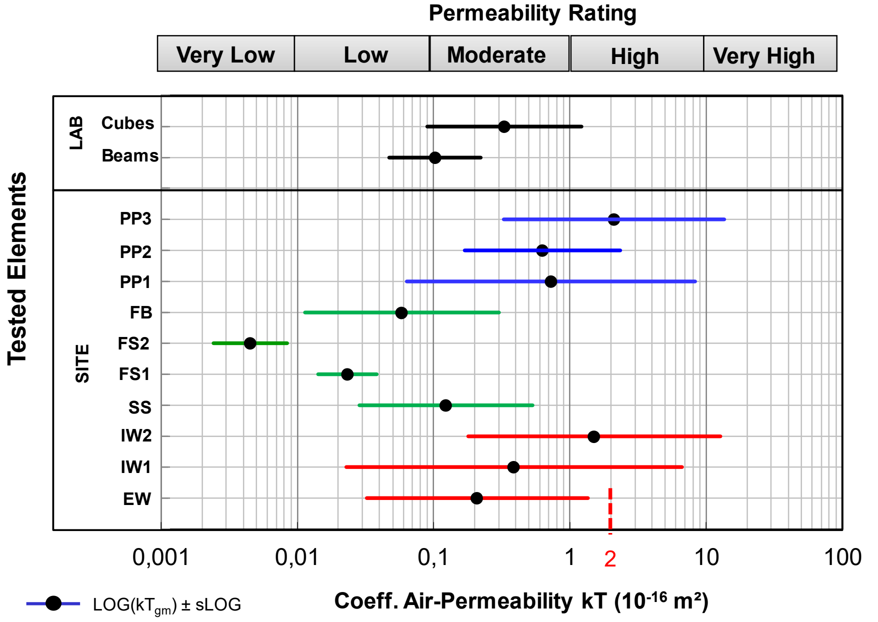

Fig. 8 – Summary of test results obtained on site (bottom) and in the laboratory (top)

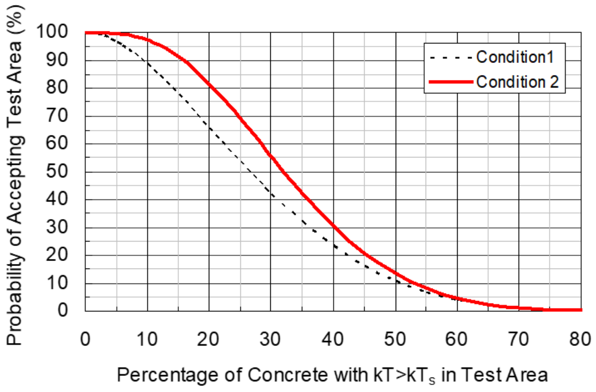

Fig. 9 – O-C Curve of the compliance criterion of Swiss Standard SIA 262/1:2013 for site air-permeability