

MODEL STANDARD FOR MEASURING THE COEFFICIENT OF AIR-PERMEABILITY kT OF HARDENED CONCRETE

This document is prepared in a format suitable for presentation before National or International Standards' Organizations. The operational aspects of the test, common to laboratory and field applications, are based on those corresponding to Annex E of Swiss Standard SIA 262/1:2019 and Argentine Standard IRAM 1892:2021; the sampling procedures for site testing, as well as the conformity assessment with specified values are also taken from those standards.

1 Object and Scope

The object of this model standard is to describe a non-destructive test method to measure the coefficient of air-permeability kT of hardened concrete, applying the double-chamber vacuum cell technique.

The method is applicable in the laboratory on concrete specimens as well as “in situ” on finished concrete elements.

The degree of water-saturation of the concrete pores affects the air-flow and, hence, the result of the test, reason why the surface moisture content of the concrete to be tested shall be measured to check that it is sufficiently low to obtain kT values that are representative of the true quality of the concrete.

2 Referenced Documents

Standards:

- ASTM F2659: “Standard Guide for Preliminary Evaluation of Comparative Moisture Condition of Concrete, Gypsum Cement and Other Floor Slabs and Screeds Using a Non-Destructive Electronic Moisture Meter”, 6p.
- IRAM 1892: “Hormigón - Método de ensayo para la determinación del coeficiente de permeabilidad al aire (kT) del hormigón endurecido”. Argentine Standard, 2021
- ISO 1920-3: “Testing of concrete — Part 3: Making and curing test specimens”
- SIA 262/1. "Construction en béton. Spécifications complémentaires". Annex E: ‘Perméabilité à l’air dans les structures’. Swiss Standard, 1 March 2019, 60 p. (also in German)

Other:

- Jacobs, F., Denarié, E., Leemann, A. und Teruzzi T., “Empfehlungen zur Qualitätskontrolle von Beton mit Luftpermeabilitätsmessungen”. Bundesamt für Strassenbau, VSS Report 641, December 2009, Bern, Switzerland
- Torrent, R., Neves, R. and Imamoto, K. (2021). "Concrete Permeability and Durability Performance - From Theory to Field Applications". CPC Press, Taylor & Francis
- User Manuals of: *Torrent Permeability Tester*, *PermeaTORR*, *PermeaTORR AC*, *PermeaTORR AC+*.

3 Significance and Use

The durability performance of concrete structures subjected to various aggressive environments depends, to a large extent, on the penetrability of the concrete pore system.

The present knowledge on suitable test methods and correlations between the individual transport parameters justifies the extensive use of gas-permeability measurements to characterize concrete transport properties. Although not directly linked to degradation, this parameter offers close correlations with the diffusion coefficient of gases, the diffusion of aggressive ions in the liquid phase, the rate of water absorption as well as with the permeability to water or diluted solutions in concrete. Therefore, this single parameter may characterize the penetrability of concrete in a variety of different cases, thereby covering various corrosion and deterioration mechanisms.

The coefficient of air-permeability of a concrete surface depends on many factors including:

- (a) concrete mixture proportions
- (b) chemical composition and physical characteristics of the binder;
- (c) characteristics of the aggregate and of the aggregate-paste Interfacial transition zone;
- (d) placement method including consolidation and finishing;
- (e) the type and duration of curing;
- (f) the degree of hydration or age;
- (g) the presence of microcracks;
- (h) the presence of surface treatments

The air-permeability is also strongly affected by the moisture condition of the concrete at the time of testing.

The coefficient of air-permeability kT is, therefore, a relevant durability indicator of the concrete tested [Torrent et al, 2012; Torrent & Ebensperger, 2013]. The background and relevance of the test method are described in detail in Chapters 5 and 8 of [Torrent, Neves & Imamoto, 2021].

Moreover, in combination with the thickness of the cover over the reinforcement, it can provide an estimate of the initiation time of steel corrosion (closely linked to the service life) by applying several models:

- ‘TransChlor’ model for chloride-induced steel corrosion, Chapter 9 of [Torrent, Neves & Imamoto, 2021]
- The ‘Exp-Ref’ method for steel corrosion of new structures, induced by chlorides [Torrent, 2013; 2015] or by carbonation [Torrent & Fernández Luco, 2014]
- Two methods for carbonation-induced steel corrosion of new structures [Kurashige & Hironaga, 2015; Belgacem et al, 2020].
- Two methods for carbonation-induced steel corrosion of old structures [Imamoto et al, 2013; Neves et al, 2018]

4 Principles of the test method

The principles of the test method are:

- a) A vacuum cell, composed of two concentric chambers is applied on the concrete surface to be tested (Fig. 1). A vacuum in the two chambers is created by a vacuum pump, the external atmospheric pressure pressing the cell onto the concrete surface and sealing the two chambers by means of two soft concentric rubber rings (Fig. 2)

- b) after 60 s, the central, test chamber (then at a pressure typically of 0 - 50 mbar) is isolated from the pump, moment at which its pressure starts to rise due to the air (at atmospheric pressure ≈ 1000 mbar) in the concrete pores flowing into the chamber through the concrete (Fig. 1)
- c) the pump continues to run, operating exclusively on the external chamber, extracting just the necessary amount of air for its pressure P_e to balance the pressure of the central chamber P_i (this is achieved by a high-precision pressure regulator); so that, at any time, $P_e = P_i$
- d) the rate of increase in pressure in the central chamber during the test, that is higher the more permeable the concrete tested, is recorded, allowing the calculation of the coefficient of air-permeability kT , by applying Eq. 1
- e) after storing the results in the instrument's memory, a venting valve is opened to restore the whole system to atmospheric pressure, moment in which the cell can be detached from the concrete surface, ready for a new test
- f) the characteristic feature of the test method is the presence of the external chamber which, keeping the same pressure as the central chamber, acts as a guard-ring. The resulting controlled flow of air into the central chamber, that can be assumed to be unidirectional (see Fig. 1), allows the derivation of Eq. 1

5 - Apparatus

5.1 Permeability Tester

The equipment for testing air-permeability basically consists of:

- a two-chamber vacuum cell composed of two concentric chambers: internal (test chamber) and external (guard-ring) and soft elastomeric rings that divide the chambers and seal the cell onto the concrete surface when under vacuum
- a control unit, consisting of valves, pressure sensors and a pressure regulator capable of keeping the pressure of both vacuum chambers permanently balanced within the tolerance $|P_e - P_i| \leq 5$ mbar (P_e = pressure in the external chamber; P_i = pressure in the internal chamber)
- a vacuum pump capable of reaching a pressure of 15 mbar or less when applied on an impermeable surface

The vacuum pump may be embedded in the instrument or may consist of a separate unit connected to the instrument.

The instrument shall carry an impermeable plate (made of metal or polycarbonate) for conditioning and calibration purposes.

5.2 Surface Moisture Meter

A device, based on the electrical impedance principle, capable of measuring non-destructively the surface moisture of the concrete within the range 0.0 – 6.9% with an accuracy of $\pm 0,1\%$, according to ASTM F2659 Standard.

5.3 Abrasive Stone or Angle Grinder

In most cases, the test can be done by applying the vacuum cell directly on the natural concrete surface (previously cleaned of dust). In some cases, it might be necessary to polish the concrete manually, using an

abrasive stone. For extreme cases of irregular surfaces (e.g. shotcrete), it may be necessary to apply an angle grinder machine (Bosch GWS 6-115 Professional or similar).

5.4 Brush, Dry Sponge or Vacuum Cleaner

To remove the dust that may have accumulated on the concrete surface. In certain occasions, especially when testing dirty horizontal surfaces like floors, it may be convenient to use a domestic vacuum cleaner.

5.5 Cover Meter (for Reinforced Elements)

To identify the position of steel bars and estimate their cover thickness. The cover thickness provides an essential input to models to assess the service life of the structures in risk of steel corrosion induced by carbonation or chlorides.

The cover meter may operate by creating a magnetic field and monitoring the change of magnetic reluctance or on the generation of 'eddy currents' due to the vicinity and size of the steel bars. Alternatively, it can be based on the electromagnetic detection of reflecting microwaves generated by the instrument, better known as Ground Penetrating Radar.

5.6 Laboratory Ventilated Oven (for Laboratory Testing)

A sufficiently large oven allowing for air circulation and capable of maintaining a temperature of $50 \pm 2^\circ\text{C}$. Used to precondition the laboratory specimens' moisture prior to the air-permeability test.

5.7 Thermometer

To measure the air and concrete temperature within the range $0 - 50^\circ\text{C}$ with an accuracy of 0.1°C .

5.8 Visual Aids

Accessories to help identifying defects (e.g. microcracks) on the concrete surface that may cause anomalous results, such as magnifying lenses, lamps, isopropyl alcohol for spraying, crack-width gauges, etc.

6 Test Objects and Testing Conditions

6.1 Type of Samples

Both for laboratory and site testing, the maximum size of the aggregate in the concrete shall not exceed 80% of the diameter of the central chamber (i.e. 40 mm for the standard cell).

Concretes made intentionally with high porosity, such as cellular or draining concrete are not suitable for testing with this method.

6.1.1 Laboratory Tests

The surface of the specimen to be tested shall have a minimum dimension of 150 mm with a minimum thickness of 50 mm.

The test can be performed on concrete cylinders, cubes or prisms. The preparation of the specimens shall be made according to ISO 1920-3 or equivalent.

Note 1: Cubes or prisms (150 mm or larger) are ideal specimens, as they present four nominally identical surfaces for testing kT .

6.1.2 Site Tests

The vacuum cell shall be placed at a distance of at least 50 mm from the nearest edge of the element and of at least 200 mm from the nearest location of other tests (distance measured from the edge of the vacuum cell).

6.1.3 Special cases

Testing specimens of 100 mm minimum size or elements of pronounced curvature requires the use of special cells or adaptors, see Fig. 3.

6.2 Curing and Age of Testing

6.2.1 Laboratory Tests

The specimens shall be moist cured according to ISO 1920-3 or equivalent for 28 days and tested immediately after completing the preconditioning process described in Section 8.4.

Note 2: Shorter periods of moist curing can be established if the effect of lack of curing wants to be investigated; in that case, it is recommended to store the specimens, after the moist curing period, in a room with RH = 75% or less. Experience indicates that little is gained in air-permeability by extending the moist curing beyond 28 days.

6.2.2 Site Tests on New Structures

For new structures, an age of testing between 28 and 180 days is recommended, with at least 7 days after the end of moist curing.

6.2.3 Site Tests on Structures in Service

The method is applicable for condition assessment and potential residual service life of structures in service, for which there are no limits on their age.

Note 3: The effect of ageing and service loads may have an impact on the test results. For this application, neither the sampling (7.2) nor the evaluation of results (10.2) are mandatory.

6.3 Temperature and Moisture Conditions

6.3.1 Laboratory Tests

After curing and before testing, the specimens shall be dried in the ventilated oven at a temperature of 50 ± 2 °C, leaving a free distance of at least 20 mm between specimens and with the walls of the oven. The drying will continue until the moisture meter indicates a surface moisture of the specimens within the range 4.0 - 5.5 % (normally this is achieved within 4 ± 2 days of drying).

Note 4: Experience indicates that the moisture can be measured when the specimens are still at 50°C temperature, without significant difference to room temperature.

The room and concrete temperature during the test shall be within the range 5 – 50° C.

6.3.2 Site Tests

The air and concrete temperature at the moment of test shall be within the range 5 – 50°C. In case of intense solar radiation, both the tested surface and the instruments shall be protected with umbrellas or canopies.

The surface moisture of the concrete at the moment of test shall not exceed 5.5% (see 8.3).

Note 5: The required moisture conditions are usually reached after 2-3 consecutive days with RH < 80% of the last contact of the element with water (rain, splash, etc.).

7 Sampling

7.1 Laboratory Tests

To characterize a given concrete, at least four air-permeability measurements shall be performed on at least two different companion specimens. This can be achieved, for instance, by testing the opposite lateral faces of two cubes or one plane face of four cylinders (testing always the same face, top or bottom surface as cast, the latter being preferable).

Note 6: The test surface (finished, lateral or bottom of the mould) may have an influence on the permeability (effects of compaction, settlement, bleeding). Therefore, it is advisable to test always the same surface of the specimens.

7.2 Site Tests

The following procedure shall be followed:

- a) Organize the structural elements in Groups, representing:
 - Same concrete type, i.e. concrete mixes that belong to the same consistency class, same strength class, subjected to the same exposure class and produced with the same constituents
 - Same nominal concreting practices (placing, consolidation, finishing, curing, etc.)
 - If specified, have the same limiting value kT_s (see 10.2)
- b) Within each Group, arrange the elements chronologically
- c) Define Lots within each Group. Each Lot will be subjected to an individual conformity decision and involves the smallest of the following surface areas:
 - 500 m² of exposed surface
 - 3 concreting days
- d) Within each resulting Lot, select randomly 6 measurement points, respecting what was stipulated in Section 6.1.2

8 Testing Procedure

8.1 Inspection of the Concrete Surface

Prior to initiating a test, the surface to be tested shall be visually inspected to check for the absence of irregularities, micro- or macro-cracks, bug-holes or other defects that may influence the measurements and invalidate the test result. Use can be made of the elements described in Section 5.8.

8.2 Condition of the Concrete Surface

If the irregularities are such that prevent attaining sufficiently low initial vacuum ($P_i < 100$ mbar), a manual or mechanical polishing of the area to be tested is required, using the elements indicated in Section 5.3.

The surface shall be free of dust, oil, grease, paint or any other substance that may affect the instrument or the test result. If the test has to be performed on a coated area, the situation shall be described in the test report.

Remove loose dust from the surface to be tested as described in Section 5.4 before applying the vacuum cell.

8.3 Determination of Surface Moisture

At each measurement point, two readings of the surface moisture meter (see 5.2) shall be performed, along approximately perpendicular directions and at about 45° of the determined or expected alignment of the steel bars. Make sure that the instrument electrodes are firmly pressed onto the concrete surface during the readings.

The result is the arithmetic mean of both readings and shall be recorded as part of the testing protocol.

8.4 Conditioning and Calibration of the Instrument

Before starting the measurements, the instrument – with the vacuum cell placed on the supplied calibration plate - must be conditioned (20 min evacuation of both chambers' pneumatic systems). This is done in order to extract moisture, volatiles, etc. that may have accumulated inside the pneumatic system.

Immediately after completing the conditioning, the instrument – with the vacuum cell always placed on the supplied calibration plate – shall undergo two successive calibrations. The data of pressure rise with time, from the last calibration, are stored in the instrument's memory. For the calculation of the coefficient of air-permeability (Eq. 1), the effective pressure rise is used, which is the difference between the pressure rise measured during the test and that recorded during the calibration at the same time.

The calibration is valid if the maximum pressure rise recorded after the 2nd calibration does not exceed 5.0 mbar and does not differ by more than ± 0.5 mbar from that of the previous calibration. If these conditions are not met, further calibration(s) shall be conducted until their achievement for two successive calibrations (Note 7).

Note 7 - Usually two calibrations are sufficient to meet the requirements, eventually three.

For laboratory testing, conducted under reasonably stable temperature conditions, just one complete conditioning + calibration process is recommended before starting the tests. In the field, it is recommended to apply this procedure twice a day, once just before starting the measurements and, again, around noon.

Note 8 - An accurate calibration is especially important for concretes of low-permeability, where a small change in the calibration pressure has a strong effect on the relatively small pressure rise due to the air coming from the sample. The calibration changes with temperature, hence the need to calibrate twice a day.

The maximum pressure rise during the calibrations shall be recorded as part of the testing protocol.

8.5 Air-Permeability Test

Just one measurement shall be performed at each measurement point, defined in 6.1.1 and 6.1.2. If the central chamber lies in coincidence with the location of steel bars, make sure that the cover thickness is of at least 20 mm.

The formula to calculate the coefficient of air-permeability kT (Eq. 1) assumes that, initially, all the pores in the concrete contain air at atmospheric pressure. Therefore, it is required to observe a waiting period of at least 30 min between successive measurements at the same point.

Note 9 – It is recommended to draw a circle around the vacuum cell with pencil, chalk or marker, in case a repetition of the test is required at the same location or in the same element (see 6.1.2 and 10.2).

9 Calculations

The coefficient of permeability to air kT of hardened concrete is expressed in m^2 and is calculated with Eq. 1.

$$kT = \left(\frac{V_c}{A} \right)^2 \cdot \frac{\mu}{2 \cdot \varepsilon \cdot P_a} \cdot \left(\frac{\ln \left(\frac{P_a + \Delta P}{P_a - \Delta P} \right)}{\sqrt{t_f} - \sqrt{t_0}} \right)^2 \quad (1)$$

where:

V_c = volume of the inner test chamber pneumatic system (m^3)

A = area of the inner test chamber (m^2)

μ = dynamic viscosity of air (N.s/m^2)

ε = open porosity of the concrete (-) which, by default is taken as 0.15

P_a = atmospheric pressure (N/m^2)

ΔP = increase of effective pressure in the inner chamber between time t_0 and t_f (N/m^2)

t_0 = time from which the increase in pressure of the central chamber is measured (60 s)

t_f = time at which the test is finished (s)

If the calculated value of kT is below $0.001 \times 10^{-16} \text{ m}^2$, it should be reported as “ $kT < 0.001 \times 10^{-16} \text{ m}^2$ ” as it is out of the accuracy limit of the instrument.

The maximum penetration depth L (mm) of the atmospheric pressure front is calculated with Eq. 2.

$$L = \sqrt{\frac{2 \cdot kT \cdot P_a \cdot t_f}{\varepsilon \cdot \mu}}$$

(2)

Both kT and L are indicated by the instrument at the end of the test, together with other relevant data.

If the penetration of the test L exceeds the thickness of the element e , kT shall be computed applying Eqs. 3 and 4. Some instruments make the calculation automatically after entering the value of e .

$$kT = \left(\frac{-b + \sqrt{b^2 - 4ac}}{2a} \right)^2 \quad \text{valid for } L \geq e \quad (3)$$

where

$$a = \frac{P_a \cdot t_f}{\mu \cdot e}; \quad b = -\sqrt{\frac{2 \cdot P_a \cdot \varepsilon \cdot t_0}{\mu}}; \quad c = \frac{e \cdot \varepsilon}{2} - \left[\sqrt{\frac{2 \cdot P_a \cdot \varepsilon \cdot kT_i}{\mu}} \cdot (\sqrt{t_f} - \sqrt{t_0}) \right]$$

(4)

Note 10. The coefficient of air-permeability (kT) is usually expressed in 10^{-16} m^2 units and ranges between $0.001 \times 10^{-16} \text{ m}^2$ and $100 \times 10^{-16} \text{ m}^2$.

Note 11. For the case of application of the test method on mortar or cement paste, it is recommended to use in Eqs. 1 and 2 the porosity ε measured experimentally. If not available, it is recommended to adopt default values of 0.25 for mortar and of 0.55 for cement paste.

Note 12. Depending on the kT of the tested concrete, t_f ranges between 75 s and a maximum of 720 s, maximum that some instruments reduce optionally to 360 s.

Note 13. At the time of publication, all available commercial instruments compute kT and L according to Eqs. 1 and 2 and report their values.

10 Evaluation of Test Results

10.1 Laboratory Tests

Based on the assumption that the distribution of test results is well represented by a log-normal distribution [Torrent et al, 2022], the central value of a series of measurements conducted on companion specimens of the ‘same’ concrete, as described in Section 7.1, is the geometric mean kT_{gm} of the four or more individual results, which is the n -root of the product of the n individual results kT_i obtained:

$$kT_{gm} = \left(\prod_{i=1}^n kT_i \right)^{\frac{1}{n}} \quad (5)$$

The scatter of the n individual kT_i results is represented by the s_{LOG} value, which is the standard deviation of the $\log_{10}$ of the individual kT_i results:

$$s_{LOG} = \sqrt{\frac{\sum_i^N (kT_i - kT_{gm})^2}{n-1}} \quad (6)$$

Using the properties of the log-normal distribution, it is possible to compute a characteristic value of the air-permeability kT_k as:

$$kT_k = 10^{(\log \log kT_{gm} + z \cdot s_{LOG})} = kT_{gm} \times 10^{(z \cdot s_{LOG})} \quad (7)$$

Where z is the argument of the normal distribution for a given probability p of finding kT values lower than kT_k in the population.

When the test is used for quality control purposes, it shall be indicated whether kT_{gm} or kT_k shall comply with the specified maximum requirement; in the latter case, a value of $z = 1$ is recommended.

Table 1 provides a classification of air-permeability from “Negligible” to “Ultra High”, as function of the kT values measured.

Table 1 – Classification of Concrete Permeability in terms of kT

kT (10^{-16} m ²)	Permeability Class	
< 0.001	PK0	Negligible
0.001 - 0.01	PK1	Very Low
0.01 – 0.1	PK2	Low
0.1 – 1.0	PK3	Moderate
1.0 – 10	PK4	High
10 - 100	PK5	Very High
> 100	PK6	Ultra High

10.2 Site Tests

In the case of site tests, the following conformity criterion should be applied to the 6 individual kT_i results obtained as described in Section 7.2, with respect to the specified kT_s limiting value:

- Not more than one kT_i result out of the 6 tests shall exceed kT_s
- If just 2 out of the 6 test results exceed kT_s , a new set of 6 tests is performed at different random places within the same lot. From this new set of 6 results, not more than one kT_i result shall exceed kT_s

If either condition a) or b) are complied with, the lot is considered in conformity with the specified kT_s value. If none of conditions a) or b) are complied with, the lot is considered not in conformity with the specified kT_s value, requiring correcting, remedial, or even compensation actions.

Table 2 presents the limiting values kT_s recommended by Swiss Standard SIA 262/1 as function of the Exposure Class and the corresponding equivalences for ACI 318.

Table 2 – Recommended limiting values kT_s as function of Swiss and ACI Exposure Classes

Exposure Classes after SIA 262/1	XC1, XC2, XC3	XC4, XD1, XD2, XF1, XF2, XF3	XD3, XF4
Exposure Classes after ACI 318	F0, S0, P0, C0	F1, S1, P1, C1	F2, F3, S2, S3, C2
Valor limite kT_s	Not required	$2,0 \times 10^{-16} \text{ m}^2$	$0,5 \times 10^{-16} \text{ m}^2$

The Operating Characteristic (O-C) Curve of the above-mentioned conformity criterion is presented in Fig. 4, which provides a clear meaning of the kT_s value. The O-C curve carries in abscissae the proportion of the concrete surface in a lot with kT higher than the specified value kT_s , i.e. the proportion of 'defective' concrete. In ordinates, the chart presents the probability of accepting a lot (applying conformity rules 1 and 2) containing a given proportion of 'defectives'.

From Fig. 4 it can be seen that a lot containing 10% of 'defectives' will have a 97% probability of being accepted, whilst for one with 50% 'defectives', the probability drops to just 13%.

11 Report

The report of a series of measurements should include the following information:

- Description of jobsite / project and ordering person/body
- Dates of concreting and of testing → Age at testing
- Mix design code or details (binder content, w/c ratio, strength class, etc.)
- Exposure condition of the elements (e.g. EN XC4 or ACI C1)
- Specified air-permeability kT_s limiting value, if any
- Ambient conditions (temperature and relative humidity). For site tests, weather conditions on the day of test and on preceding two days
- Maximum pressure rise during 1st and 2nd calibration (ΔP_{C1} and ΔP_{C2}); for site tests, in the morning and around noon
- Data on the operator/s and instruments used
- For each test:
 - Instrument's sequence test (for easy identification of data in its memory)

- Lot and specimens or elements investigated
- Location of measurement point
- If measured, cover thickness at the measurement point
- Temperature of the concrete
- Surface moisture of concrete
- Reported anomalies (cracks, bug-holes, coatings, need of polishing, etc.)
- Individual test results kT_i and penetration depths L (indicating eventual thickness correction)
- Geometric mean kT_{gm} and s_{LOG} of the individual test results. Optionally, graphical presentation of results as described in Section 5.8.2.

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