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Empfehlungen zur Qualitätskontrolle von Beton mit Luftpermeabilitätsmessungen

Recommandations pour le contrôle de la qualité du béton au moyen de mesures de perméabilité à l'air

Recommendations for the quality control of concrete with air permeability measurements

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Recommendations for Quality Control of Concrete with Air-Permeability Measurements

Translation into English of Chapters 1 and 2 and Annex D by

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1 Introduction

1.1 General

Over the last decades it has been recognized that the damages to reinforced concrete structures are mainly caused by insufficient durability rather than by low strength. In most cases, the quality and thickness of the cover concrete determine the durability of the structure. Since the quality of the cover concrete is influenced not only by the mix composition but also by the placing and the curing conditions, it is appropriate to measure the achieved quality on the structure rather than on separately cast specimens. In addition, due to the use of relatively slow-reacting cements and mineral additions, an inadequate curing may lead to worsening the quality of the cover concrete. The suitability of the w/c ratio to characterize the quality of concrete has been affected in the last years by the increase in variety of cement types and mineral additions in use. More details are given in Annex A.

Ideally, the quality of a concrete construction should be evaluated on site, rather than on separate cast specimens, due to the differences in compaction, curing, etc.

Gouws et al. (2001) investigated construction elements on site and on separate cast specimens finding that, in average, the water sorptivity and chloride resistance of the specimens were ¼ and ⅓, respectively, smaller than in the corresponding concrete elements. SIA Standard 262 requests the determination of the quality of the cover concrete, indicating for that the site Air-permeability test (see Annex A).

The multiplication of requests to determine the “impermeability” of concrete on structures will eventually lead to changes in the construction process, towards more care being dedicated to the placing and curing of concrete. It will also foster the use of methods to improve the tightness of cover concrete (such as Controlled Permeability Formwork liners or vacuum dewatering) and thus extend the durability of structures.

Ideally, the investigation at the jobsite should be conducted as early and non-destructively as possible. If the results indicate that the specifications of the concrete have not been met, the causes are to be established and appropriate corrective actions undertaken for the rest of the construction process. Moreover, at this early stage when no damages still exist, further measures to ensure the achievement of the planned service life of the construction can be decided, such as further investigation, application of a surface protective system, etc.

1.2 Objective and Content

The following objectives were established:

- Preparation of Recommendations for the determination of Air-permeability according to SIA 262/1
- Round-robin test on concrete elements to establish statistical values for he determination of Air-permeability on site according to SIA 262/1

Chapter 2 presents recommendations to determine the Air-permeability according to SIA 262/1, from tendering to evaluation of conformity. Annex B presents detailed explanations on the method to determine of Air-permeability according to SIA 262/1, as well as on important influencing factors on the Air-permeability measurement such as concrete temperature and moisture. Information on the accuracy of the method is also given. Annex C presents the results of the Round-robin Air-permeability tests performed on two jobsites and the statistical evaluation of the results. Annex D provides background information on the proposed conformity evaluation criterion.

2 Recommendations for the Quality Control with Air-permeability measurements according to Swiss Standard SIA 262/1

2.1 Preliminary Remarks

The recommendations here provided are based on the Authors' to date experience with the Air-Permeability test method (instruments of the companies Proceq and Materials Advanced Services) on conventional concretes according to SN EN 206-1. The recommendations correspond to "usual" measurements; those performed for special purposes or under special conditions may depart from these recommendations.

The recommendations contain information on:

- the selection and preparation of the measurement points (Section 2.2)
- the conformity that the requirements have been fulfilled (Section 2.3)
- the necessary environment conditions (Section 2.5)
- the preparation of the test instrument (Section 2.6)
- the execution of the measurements (Section 2.7)
- quotation of the measurements (Section 2.8)

2.2 Selection and Preparation of the Test Areas and Measurement Points

The structure to be investigated should be divided into Groups of elements that have the following in common:

- same specified Air-permeability
- same concrete type, e.g. same exposure class, compressive strength class and maximum size of aggregate
- were built under essentially the same concreting conditions, i.e. placement, compaction and curing methods, etc.

For each construction site under investigation, the elements belonging to each Group should be listed chronologically according to the date of concreting.

Each Group consists of several construction elements/sections from where one or more Test Areas should be selected.

The quantity of Test Areas is established according to the following two criteria:

- 1 Test Area per each 500 m^2 of exposed concrete surface or extra fraction thereof
- 1 Test Area per each 3 days of concreting

The criterion that yields the larger amount of Test Areas is to be adopted.

Fig. 1 shows an example of the selection of the Test Areas.

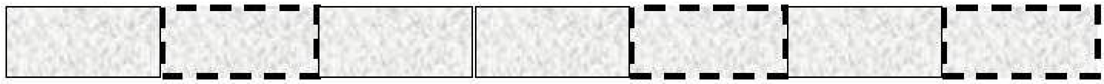
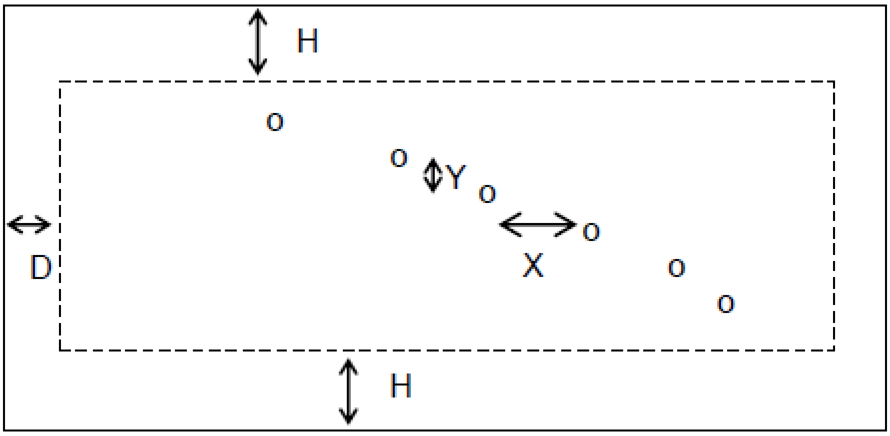


Fig.1 – Example of the selection of Test Areas on 7 tunnel elements (60m^2 each), built at a rate of 1 per week; the areas marked with broken lines are the selected Test Areas

On each Test Area, 6 Measurement Points are established at random, according to the following recommendations:

- Sufficiently apart, both horizontally and vertically, from edges, joints (construction or concreting), openings, etc. (Fig. 2). This is because the quality of the concrete element is usually worse near the edges. In cases where the quality near the edges is to be established, then this recommendation does not apply.
- The Measurement Points should be separated from each other, at least 200 mm both in the horizontal and vertical direction; moreover, measurements on vertical or horizontal visibly poor zones (e.g. cracks, bad concreting joints) should be avoided. Of course, if the inspection is specifically oriented to such areas, tests can be conducted on them.



o: Measurement Point; H > 150 mm, D > 50 mm, X and Y > 200 mm

Fig. 2: Recommendations for selecting the Measurement Points on a concrete wall.

For the selection of the Measurement Points, the following should be observed:

1. Surface Protection Treatment (SPT): A first step is to check visually whether a SPT has been applied. If a SPT is detected, if possible it should be locally removed from the selected Measurement Point before performing the test. Alternatively, it could be checked whether the SPT has an influence on the air-permeability (measuring with and without the SPT). In case of doubt on the presence and/or influence of the SPT on the Air-permeability no measurements should be conducted or, if they are performed, the circumstance should mentioned in the test report (e.g. “SPT on the concrete, influence on Air-permeability unknown”).
2. Re-bars cover depth: It should be controlled that there are not re-bars, cable ducts or pipes closer than 20 mm from the concrete surface at the Measurement

Point. If this cannot be avoided, the circumstance should mentioned in the test report

3. Concrete surface: According to the limited current experience, it is possible to measure the Air-permeability in construction elements built with static formwork as well as with slip-forms, provided that the surface is sufficiently smooth[1]. If the surface shows too much roughness, it can be manually polished with care.
4. De-dusting: Before starting the Air-permeability test, the surface shall be de-dusted with a hard brush or with a hard, dry sponge, to eliminate the adhered dust.
5. Measurement Points with cracks should be avoided, i.e. the Measurement Points should previously be inspected for cracks, e.g. by spraying the zone with an alcohol solution.
6. The Measurement Points should be marked on the surface (e.g. pencil or chalk), to avoid that two measurements are conducted on the same spot and to give the chance for further investigation in case of outliers.

2.3 Specification of Air-Permeability Values

Depending on the concrete types, according to Swiss Standards SIA 118/262, limit values of Air-permeability (kTs) of 0.50 and 2.0 10^{-16} m^2 are recommended (Table 1). As described below and deepen in Annex D, the Air-permeability limit value is not an absolute limit, but a statistical maximum value.

For concrete types A and B no limit values of Air-permeability are proposed, because the risk of steel reinforcement corrosion is rather low. For concretes subjected to Exposure Class XD2a[2] the limit value of 2.0 10^{-16} m^2 applies, whilst for those subjected to Exposure Class XD2b the limit value of 0.5 10^{-16} m^2 is recommended.

Table 1 – Proposed limit values of the Air-permeability (kTs) as function of the concrete types (SIA Standard 118/62, Revision 2009)

	Concrete Types						
	A	B	C	D	E	F	G
Strength Class	C25/30	C25/30	C30/37	C25/30	C25/30	C30/37	C30/37
Exposure Classes (CH)[3]	XC1 XC2	XC3	XC4 XF1	XC4 XD1 XF2	XC4 XD1 XF4	XC4 XD3 XF2	XC4 XD3 XF4
Minimum Cement [kg/m^3]	280	280	300	300	300	320	320
Maximum w/c ratio	0.65	0.60	0.50	0.50	0.50	0.45	0.45
Recommended kTs [10^{-16} m^2]	-	-	2.0	2.0	2.0	0.50	0.50

[1] M-A-S Note: the Air-permeability has been measured also on finished surfaces, such as airport and road pavements, tunnel slabs and industrial floors

[2] M-A-S Note:The Swiss Standard subdivides EN 206-1 Exposure Class XD2 into two subclasses: XD2a (for Cl^- concentration ≤ 0.5 g/l) and XD2b (for Cl^- concentration > 0.5 g/l)

[3] M-A-S Note: The Exposure Classes correspond to the National Swiss Version (CH) of EN 206-1, see Appendix.

2.4 Evaluation of Conformity

Each Test Area must satisfy the following conditions:

Condition 1: Out of the 6 Air-permeability values kTi, measured on a Test Area, not more than 1 can exceed the specified Air-permeability limit value kTs.

In case that just 2 out of the 6 Air-permeability values kTi, measured on a Test Area, exceed the specified Air-permeability limit value kTs, another 6 further Air-permeability tests can be conducted on 6 new Measurement Points selected from the same Test Area (see Section 2.2).

Condition 2: Not more than 1 Air-permeability value kTi out of the 6 new determinations can exceed the specified Air-permeability limit value kTs.

If neither Condition 1 nor Condition 2 is satisfied, the Test Area is considered as not in conformity with the specifications. In this case, it is recommended to:

1. Collect and evaluate all available information on the concrete quality and assess the results in view of the planned use of the construction; as a result, for instance, a further investigation of the construction element or a remedial measure can be proposed.
2. Further investigate the construction element through, for example, non-destructive measurement of the cover depth; as a result, for instance, a further investigation of the construction element (e.g. tests on drilled cores) or a remedial measure can be proposed.

2.5 Age, Temperature and Moisture of the Concrete

When Air-permeability measurements are conducted on a construction element, the following is recommended:

- Age of concrete
  - The age of concrete when tested should be between ca. 28 and 90 days. In particular, when slow-reacting cements (e.g. CEM III/B) or significant amount of slow-reacting mineral additions such as fly-ash are used, a minimum age of concrete of 2 months should be considered.

The Air-permeability is strongly affected by the moisture content of the concrete and by extreme temperature conditions (See Annex B-2). Therefore, the following conditions at the moment of test should be observed:

- Temperature of the construction element
  - The surface temperature of the construction element, measured for instance with an infrared thermometer, should be above 10°C. Experienced users can, if necessary, measure at temperatures between 5 and 10 °C.[4]
- Moisture content of the concrete, assessed by one of the following methods
  - The moisture content should not exceed 5.5 % (by mass) when determined with the CME (manufactured by Tramex, based on measuring the electrical impedance)
  - The electrical resistivity, measured by the Wenner probe (manufactured by Proceq) shall not be below 10 or 20 kΩ.cm at 20°C. The lower value applies to

[4] M-A-S Note: No upper temperature limitations have been established; however, direct exposure of the instrument, in particular the pressure regulator, to the sun should be avoided by proper sheltering

concretes manufactured with CEM I without reactive mineral additions such as fly-ash.
In case the temperature is below 15°C or above 25°C, a conversion of the electrical resistivity to 20°C should be made. If data of the variation of the electrical resistivity with temperature are not available for the investigated concrete, the following rule can be applied:
between 5 and 40°C the electrical resistivity is halved for a temperature increase of 20°C.

Whenever possible, it is recommended to apply always the same method to assess the moisture.

The achievement of the above conditions for the moisture content of the concrete depends strongly on the ambient conditions (e.g. air temperature) and will be generally be reached when:

- the curing ended 3 to 4 weeks prior to the test
- more than 2 - 5 days have passed after the last ingress of water in the concrete by, for instance, rain, spray or thaw.

2.6 Instrument's Conditioning, Calibration and Control

Before start measuring the Air-permeability, the instrument should be conditioned and calibrated. Both should be performed on each day of measurement. If it suspected that the instrument is not working properly, a new conditioning and calibration should be performed.

During measurement breaks it is recommended to place the vacuum cell on an impermeable material (e.g. metal, polycarbonate) and keep the system under vacuum.

Conditioning means placing the vacuum cell on a suitable impermeable material (e.g. metal, polycarbonate) and to evacuate the whole system for at least 15 minutes.

Calibration means placing the vacuum cell on a suitable impermeable material (e.g. metal, polycarbonate) and following the entire calibration procedure. An increase in pressure will be observed, due to small leaks and to the presence of volatile substances in the system. The pressure rise will be automatically deducted by the instrument from the values measured during the tests.

Minimum two calibrations should be conducted meeting the following conditions:

- During the second calibration the pressure rise should not exceed 5 mbar.
- The difference between the maximum pressure rise obtained in two successive calibrations should not exceed 0.5 mbar.

These conditions are usually achieved after Conditioning plus 2 – 3 Calibrations.

The duration of the Conditioning and Calibration processes is usually less than one hour.

In larger intervals (weeks – months) or if in doubt of the test results, Control measurements shall be conducted on porous inert materials of known Air-permeability to check the correct functioning of the instrument. Suitable porous inert materials are clay tiles, old concrete specimens and natural stones.

2.7 Conducting the Test

The concrete moisture and air-permeability should be determined on the 6 Measurement Points selected as for Section 2.2.

The location and results of the measurement (Air-permeability and moisture of concrete) should be, together with other indications regarding the construction element, should be reported in a test protocol. If necessary, a sketch illustrating the location of the Measurement Points could be advantageous. In next page, an example of a Test Report is presented.

If 6 new Measurement Points to measure the Air-permeability have to be selected from the same Test Area, the hints of Section 2.2. should be observed.

2.8 Quotation

The actual cost of the measurements depends strongly on the accessibility to the individual Measurement Points. Consequently, the following should be indicated:

- how close (distance in meters) to the construction element it is possible to drive
- whether the walk from the vehicle's parking place to the construction element is levelled and free of obstacles (otherwise the situation should be described)
- whether the Test Areas of the construction element is accessible (i.e. maximum 2 m high) from the floor or scaffolding, etc.
- whether site electric power (220 V required to operate the vacuum pump) is available and at what distance from the Test Areas

Example

At the construction site ……………, the Air-permeability according to SIA 262/1-E is to be measured on construction element(s) ……….., Stage …………… . The Air-permeability will be measured at 6 Measurement Points of the construction element(s) where the geometric conditions of VSS-Report No. 641 "Recommendations for Quality Control of Concrete with Air-Permeability Measurements" apply. It is possible to drive a vehicle directly inside the jobsite. Neither a ladder nor scaffolding is required for these measurements. Connection to 220V power supply is accessible at a radius of …. m. The Measurement Points have been de-dusted with a dry brush prior to the tests. The measurements can only be performed when the concrete temperature and moisture conditions indicated in the above-mentioned VSS Report are met. Therefore, the test date should be agreed with the Construction Head between ………. and ……….. . At each Air-permeability Measurement Point the concrete moisture is to be assessed with a suitable instrument, e.g. by measuring the electrical resistivity or directly with an impedance moisture meter. The air and concrete temperature should be measured at least at the beginning and end of the Air-permeability measurements. The results of the air-permeability tests should be evaluated on the spot to decide whether 6 further measurements are required in the same Test Area. The test report should conform to the example presented in the already mentioned VSS Report.

Test Report for Air-permeability after Standard SIA 262/1- E

Ordered by:……………………………………………………………………………………………
Jobsite:……………………………………………………………………………………………………
Construction element: ……………………………………………………………………………………..
Concrete Composition / Properties:………………………………………….……………
Date of Concreting of the element:…………………………………………………………………….

Element exposure to weather:...
Weather last 2 days:……………………………………………………………..………………..
Weather during test:…………………...

Air temperature	at …. hour	… °C	at …. hour	… °C
Element temperature	at …. hour	… °C	at …. hour	… °C

Measured on ……….. from …. until …. hour
Measured by: …………………………. Company: ……………………………………

Air-permeability Instrument: ……………………………………………………..
Moisture meter: ………………………………………………………………….

Preparation of the Surface (e.g. polishing):……………………………………………………
Remarks (existence of cracks, surface protection systems, etc.): …..………………
……………………………………………………………………………………………….………………
Results of the Calibration………………………………………………………………………

Measure-ment Point [-]	Centre of Vacuum cell: Distance from ………… [m]	Centre of Vacuum cell: Height from Floor [m]	Instrument Test No. [-]	Air-permeability kTi [10^{-16} m^2]	Elect. Resistivity [kΩcm]	Moisture content [%]	Comments

Number of results > kTs: …..	kTs = ….. 10^{-16} m^2	Conformity: Y / N

Number of results > kTs: …..		Conformity: Y / N

Conditions for Measurement acceptable: Y / N / partly due to ………………………

Remarks	Signature

Annex D: Considerations on the Evaluation of Conformity

D-1 Earlier Proposals for Conformity Evaluation

Several researchers have shown that the individual kT values of site concrete follow a log-normal distribution (Torrent 2001; Brühwiler et al. 2005, Conciatori 2005, Denariè et al. 2005, Quoc et al. 2006, Misak et al. 2008) (Fig. D-1). Jacobs and Hunkeler (2006) found that sometimes the log-normal distribution may be multimodal.

Therefore, the specified values and the compliance criterion proposed are based on the logarithms rather than on the kT values recorded. Hence, the characterization of a given series of tests should be done through their geometric mean rather than through their arithmetic mean. A further advantage of the geometric mean is that is less affected by isolated high values.

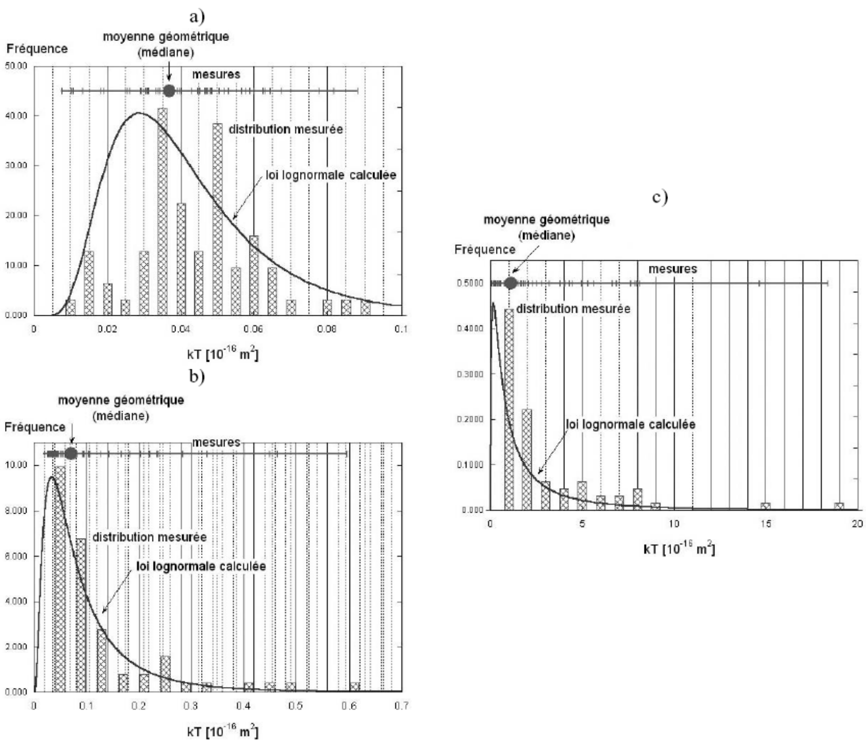


Fig. D-1: Distribution of Air-permeability test results from three jobsites with w/c ratios of a) 0.42, b) 0.52 and c) 0.73, Conciatori (2005)

Two extreme alternatives for Conformity Evaluation were considered, namely:

- Specification of a Mean Value (Torrent and Frenzer 1995)
  - Compliance is achieved if the geometric mean kT_{gm} of all results in a Test Area does not exceed the specified value kT_s

- Specification of a characteristic value (Brühwiler et al. 2005, Denariè et al. 2005, Jacobs 2006):

  $\log_{10}(kT_{gm}) + \lambda(p,N)\ .\ sLOG \leq \log_{10}(kT_s)$

where:

kT_{gm}: Geometric mean of the N individual values of kT_i recorded [10^{-16} m^2]

$\lambda(p,N)$: Factor that takes into account the proportion of "defectives" p ($kT_i > kT_s$) and the number of test results; Jacobs (2006) proposes λ □= 1

sLOG: Standard deviation of the $\log_{10}$ of kT values expressed in [10^{-16} m^2]

kT_s: Limiting value of kT specified [10^{-16} m^2]

After investigating 52 concrete elements (mostly younger than 1 year), Jacobs (2006) found that sLOG varied between 0.09 and 1.13, with an average of 0.43 (Fig. D-2)

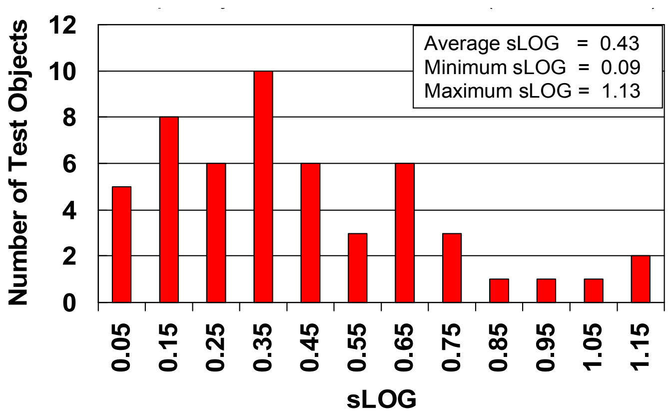


Fig. D-2: Standard deviation sLOG from 52 concrete elements, Jacobs (2006)

The approach of specifying the geometric mean has the disadvantage that the variability of the Air-permeability measurements is not considered in the compliance criterion. This means that 50% of the test results will exceed the specified geometric mean. Therefore, the quality of the concrete element will be only inaccurately assessed.

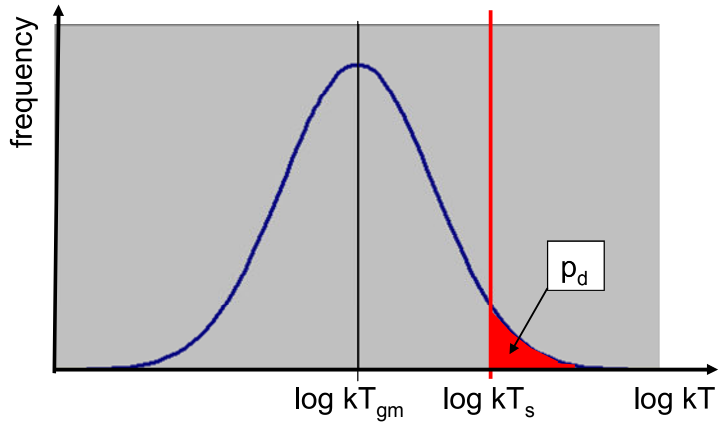
A conformity criterion based on a characteristic value has been applied in the EN Standard 206-1 for evaluation of compressive strength and by Alexander et al. (2008) for several durability indicators. The specification of a characteristic value is theoretically ideal, because the proportion of acceptable "defectives" (too high air-permeability values) is clearly defined. Two problems arise with this approach:

- Establishing the value of factor λ is not easy
- Understanding the approach, involving the calculation of the geometric mean and standard deviation of logarithms, will create difficulties in practice

D-2 Considerations on the Proposed Conformity Evaluation

The Conformity Evaluation criterion proposed is based on testing a double random sample.

Fig. D-3 shows a normal distribution of the logarithms of kT_i having a certain geometric mean kT_{gm}, a limiting value kT_s and a certain proportion of "defectives" p_d (values with $kT > kT_s$).



$$\log kT_{gm} = \log kT_s - t(p_d) * sLOG$$

Fig. D-3: Normal distribution of logarithms of kT with a proportion p_d of "defectives" ($kT > kT_s$)

To compute the probability of accepting a Test Area, we have to resort to the Binomial Distribution, which tells us what is the probability P(k) of getting k values of kT_i higher than kT_s out of a series of 6 random measurements, from a population having a proportion of "defectives" p_d. According to the Binomial Distribution, P(k) is given by:

$$P(k) = \binom{6}{k} p_d^k (1 - p_d)^{6-k}$$

with k = 0, 1, 2, 3, 4, 5, 6.

Fig. D-4 shows the corresponding binomial distributions for p_d = 5, 16, 50 and 80%.

Condition 1 of the Conformity Criterion states that in the first random sample not more than 1 value of kT (out of 6) can exceed kT_s. The probability of acceptance for that condition is P1 = P(0) + P(1). In Fig. D-4 this value (P1) is represented by the top level of the white bar (values indicated). It shows that the probability of acceptance (not more than 1 out of 6 test results above kT_s) drops from 96.7% for p_d=5% to 0.2% for p_d=80%.

Condition 2 of the Conformity Criterion states: when just 2 test results of kT_i exceed kT_s, 6 further measurements can be performed, with not more than 1 of the new 6 test results exceeding kT_s. Applying again the Binomial Distribution, the probability of acceptance for the second condition (P2) can be expressed as:

P2 = P(2) * [P(0) + P(1)]

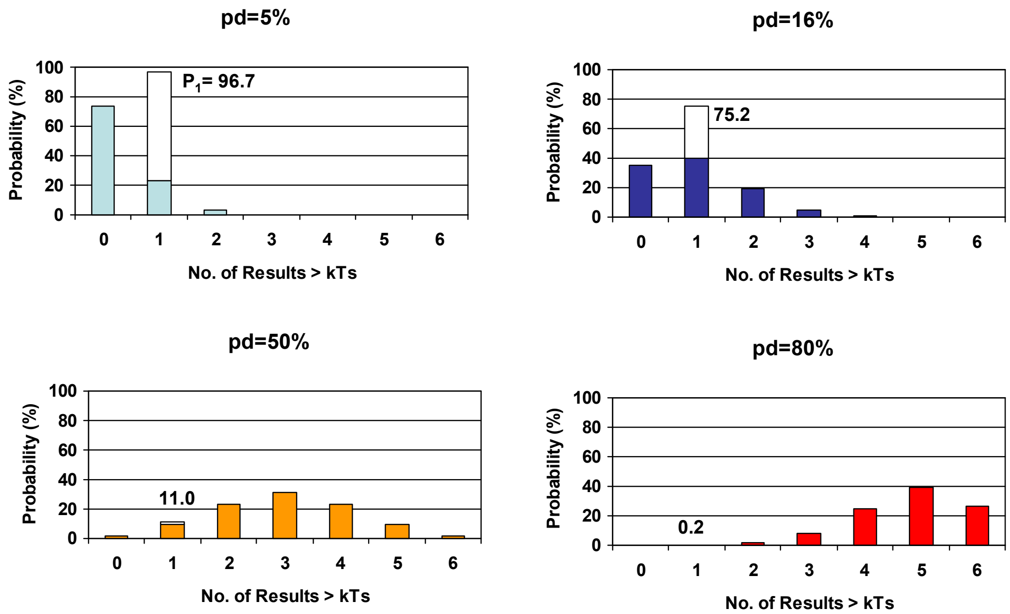


Fig. D-4: Binomial distribution for 6 tests for different proportions p_d of "defectives"

P2 is equal to the probability of getting 2 high kT_i values in the first set, i.e. P(2), multiplied by the probability of getting less than 2 high kT_i values in the second set [P(0) + P(1)].

Therefore, the probability that a Test Area is accepted is:

Pa = P1 + P2 = [P(0) + P(1)] + P(2) * [P(0) + P(1)]

Fig. D-5 shows the probability of accepting a Test Area as function of the proportion p_d of "defectives" ($kT > kT_s$) that it contains.

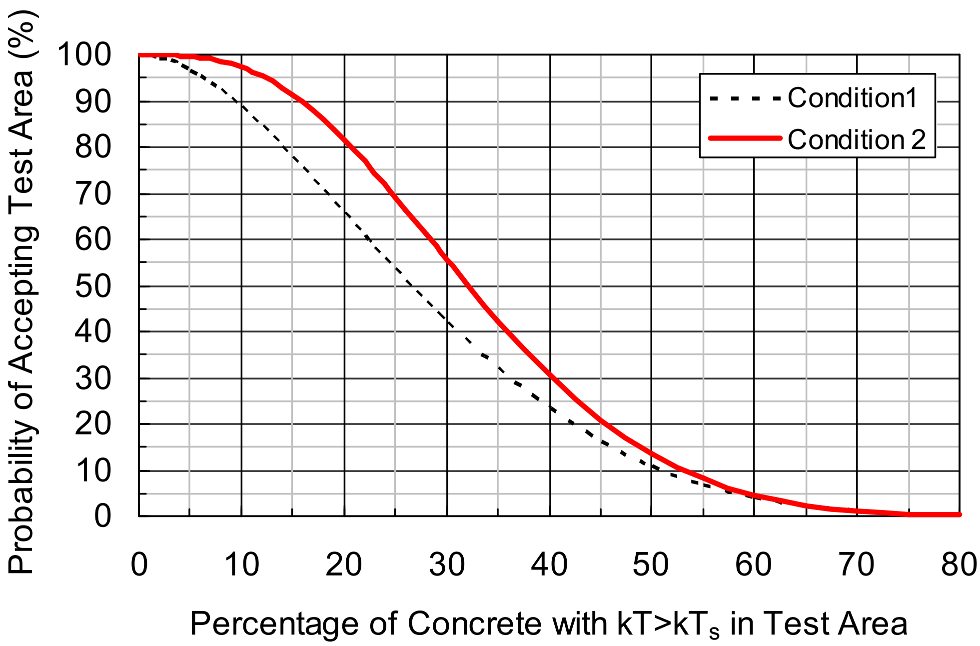


Fig. D-5: Probability of Acceptance Curve for the proposed Conformity Criterion [5]

[5] M-A-S Note: These curves have been recalculated and the red curve is slightly different to that included in the original report.

The dotted line shows the probability of acceptance in the first series of 6 tests (Condition 1) and the red continuous line the probability of acceptance after the second series of 6 tests (Condition 2). It can be seen that a probability of acceptance of approximately 95% is expected for a Test Area containing 12% of "defectives" (concrete with $kT > kT_s$)[5].

Fig. D-6 shows the kT_{gm} / kT_s ratio required to achieve a given Probability of Acceptance for various standard deviations sLOG. For kT_{gm} = 0.5 kT_s and a sLOG = 1.0, the probability of accepting the Test Area is about 35%, whilst for sLOG = 0.4 it rises to 75%. Table D-1 presents the kT_{gm} / kT_s ratios that would yield Probability of Acceptances of 80, 90, 95 and 99% for different sLOG values. The highlighted kT_{gm} / kT_s ratio = 0.34 is that providing a 95% of probability of accepting a Test Area for the average standard deviation sLOG = 0.40. This means that out of 20 Test Areas having such quality (kT_{gm} / kT_s = 0.34 and sLOG = 0.40 → p_d = 12%), 19 will be accepted and just one would be rejected.

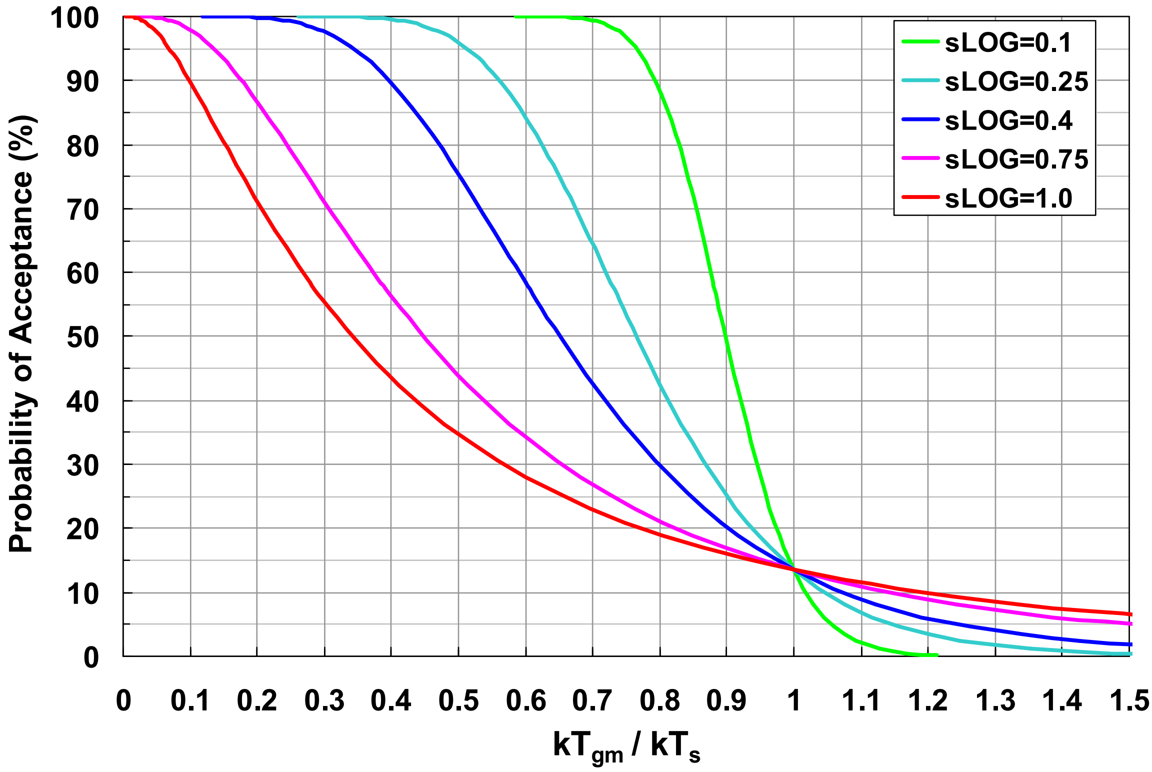
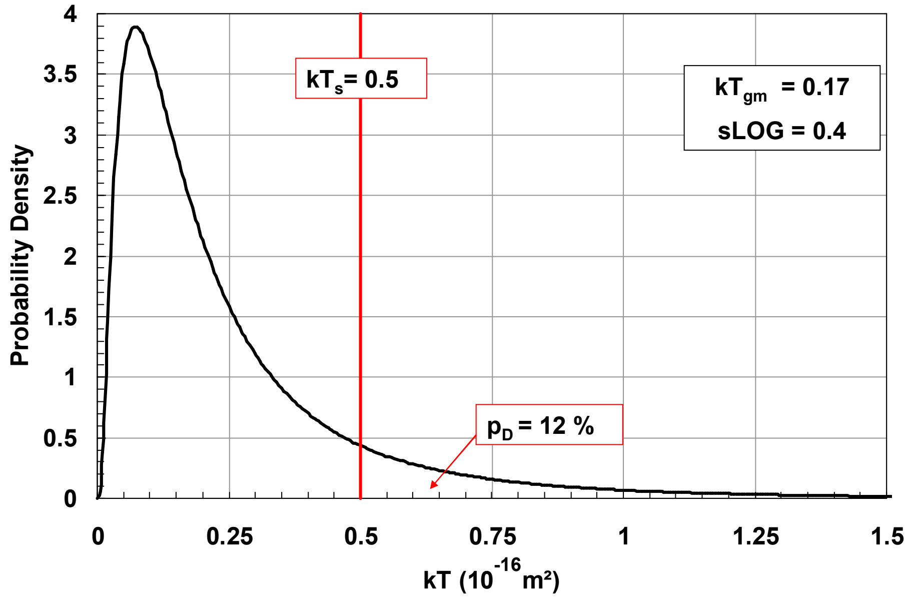


Fig. D-6: Probability of Acceptance as function of kT_{gm} / kT_s ratio and standard deviation sLOG

Table D-1 - Ratio kT_{gm} / kT_s for various Probabilities of Acceptance as function of sLOG

Probability of Acceptance (%)	kT_{gm}/kT_s for sLOG =				
	0.10	0.25	0.4	0.75	1.00
99	0.71	0.43	0.26	0.081	0.035
95	0.77	0.51	**0.34**	0.13	0.069
90	0.79	0.56	0.40	0.18	0.10
80	0.83	0.62	0.47	0.24	0.15

The probability density distributions for 95% of Probability of Acceptance and sLOG = 0.40 are shown in Fig. D-7 for the recommended specified values kT_s = 0.5 and 2.0 10^{-16} m².



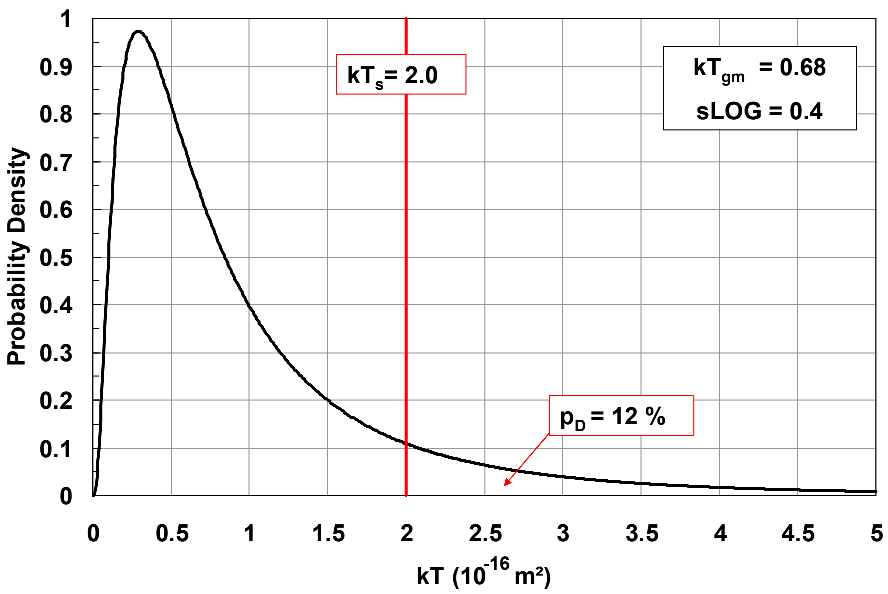


Fig. D-7: Probability Density distributions of kT for Probability of Acceptance 95% and sLOG = 0.40, for kT_s = 0.5 10^{-16} m² (top) and 2.0 10^{-16} m² (bottom)

The quantity of 6 measurements to evaluate a Test Area was, based on existing experience, considered suitable to differentiate concrete qualities (see e.g. RILEM Comparative Test, Torrent and Luco) and also the not too high variability in the tested bridge (see Fig. C-7).

The fact that up to 1 test result above the limit value kT_s out of 6 is accepted means that kT_s is a characteristic value rather than an absolute maximum limit. As shown in Fig. D-5 and D-7, a 95% probability exists of accepting a Test area with 12% "defectives", which is higher than the 5% "defectives" for compressive strength in EN 206-1 Standard. However this is reasonable because an insufficient strength has more serious consequences than an insufficient durability. It should also be mentioned that points with kTi > kTs do not necessarily correspond to low durability, as they may result from fine cracks or segregation that normally do not significantly influence durability.

D-3 Considerations on the Limiting Values

Based on the existing experience on Air-permeability measurements on laboratory-prepared concrete and on concrete elements on site, limiting values associated with exposure classes of typical concretes according to Swiss Standard SIA 118/262 (Revision 2009) were established. As shown in Fig. B-11, concrete under exposure class XD3, with air-permeability below 0.1 10^{-16} m² (geometric mean measured after decades) present acceptable levels of chloride penetration. Brühwiler (2008) proposes the same value of air-permeability. Fig. B-10 shows that a maximum air-permeability of 0.5 10^{-16} m² (geometric mean measured after decades) ensures a tolerable carbonation depth. Teruzzi (2009) arrived at a similar value based on investigation of a building. To arrive from these mean values to a limit for Air-permeability, the former have to be multiplied by a factor of 3, assuming sLOG = 0.40 and 95% probability of acceptance (Fig. D-6). Hence the reason for limiting the air-permeability to kT_s = 2.0 10^{-16} for exposure classes XC4 and XD1/XD2 and to 0.5 10^{-16} m² for exposure class XD3. For larger standard deviations (variation of quality in the concrete element), the value of the geometric mean should also be lower.

Fig. D-8 shows the proposed limiting values kT_s and experimental Air-permeability test results (geometric means). For a better comparison, the geometric means corresponding to the limit values are calculated assuming an average standard deviation sLOG= 0.40 ($kT_s = 3 . kT_{gm}$).

It is shown that most of the test results comply with the requirements for geometric mean (dotted lines). Laboratory concretes almost invariably comply (only 3 out of 24 concretes with w/c ≤ 0.50 not complying). On the contrary, for site concrete a higher proportion of results exceeding the limits is observed (16 out of 52 concretes with w/c ≤ 0.50).

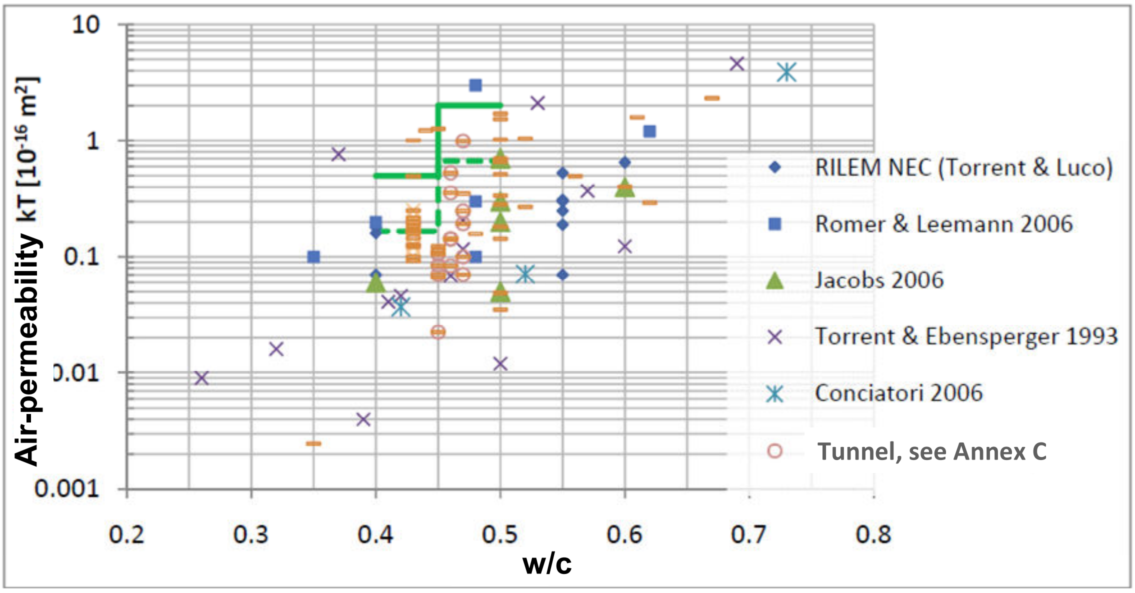


Fig. D-8: Proposed limiting values and geometric mean values from published research; orange symbols correspond to test results of concrete structures tested on site

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Appendix[6]

Exposure Classes according to Swiss National Version of Standard EN 206-1

Exposure Class	Environmental Influences	Examples
Reinforcement corrosion in carbonated concrete		
XC1	Dry or permanent wet	Structural members inside buildings at low humidity
XC2	Wet, rarely dry	Surfaces wetted with water over long periods
XC3	Moderately damp	Structural members inside buildings at moderate or high humidity, outdoor surfaces protected from rain
XC4	Alternatively wet and dry	Surfaces wetted with water which are not classified under class XC2
Reinforcement corrosion induced by chlorides (e.g. de-icing agents)		
XD1	Moderately damp	Structural members within spray range of road surfaces
XD2a	Wet, rarely dry.	Swimming pools, structural members in contact with industrial waste water containing chlorides; ≤ 0.5 g/l Cl
XD2b	Wet, rarely dry	Swimming pools, structural members in contact with industrial waste water containing chlorides; > 0.5 g/l Cl
XD3	Alternatively wet and dry	Parts of bridges, parking levels or retaining walls which are exposed to spray containing chlorides
Damage to concrete due to frost action, with or without de-icing agents		
XF1	Moderate water saturation, without de-icing agents	Vertical surfaces which are exposed to rain and frost
XF2	Moderate water saturation, with de-icing agents	Vertical surfaces which are exposed to spray containing de-icing agents
XF3	High water saturation, without de-icing agents	Horizontal surfaces which are exposed to rain and frost
XF4	High water saturation, with de-icing agents	Bridge slabs which are exposed to de-icing agents; surfaces which are exposed to spray or splash water and frost

[6] M-A-S Note: Not included in original document, shown here for those not familiar with Swiss National Version of EN 206-1