

Moisture Meters to be Used in Conjunction with the *PermeaTORR*

It is a well-known fact that the gas-permeability of concrete is strongly dependent on its degree of saturation, since high water content in the pores will hinder the flow of gas and show an artificially low gas-permeability.

Current Swiss (SIA 262/1:2019) and Argentine (IRAM 1892:2022) specify a maximum moisture content of 5.5% for site testing; the latter specifies the range 4.0% – 5.5% for laboratory specimens oven-dried at 50°C.

The above-referred values correspond to measurements of the surface moisture by electrical impedance-based instruments (ASTM F2659), specifically to those manufactured by Tramex in the Republic of Ireland. This family of instruments measures moisture values between 0% (specimens oven-dried at 105°C) and 6.9% (specimens that are fully saturated). Instrument models successfully used in connection with the *PermeaTORR* are:

- Concrete Encounter CME4, with an analogic display (see Fig. 1)
- CMExpert II, with a digital display (see Fig. 2)
- CMEX 5, with digital display and other functionalities (see Fig. 3)

More information in <http://www.tramexmeters.com>

It is strongly recommended to always use a surface moisture meter in conjunction with the *PermeaTORR*.

The two papers attached at the end of this document present:

- long-term data of surface moisture and air-permeability kT of several concretes made with wide different binders
- the research, based on which the *PermeaTORR AC+* performs a compensation of the value kT , measured at a certain moisture m to the reference moisture content of $m = 5.0\%$.



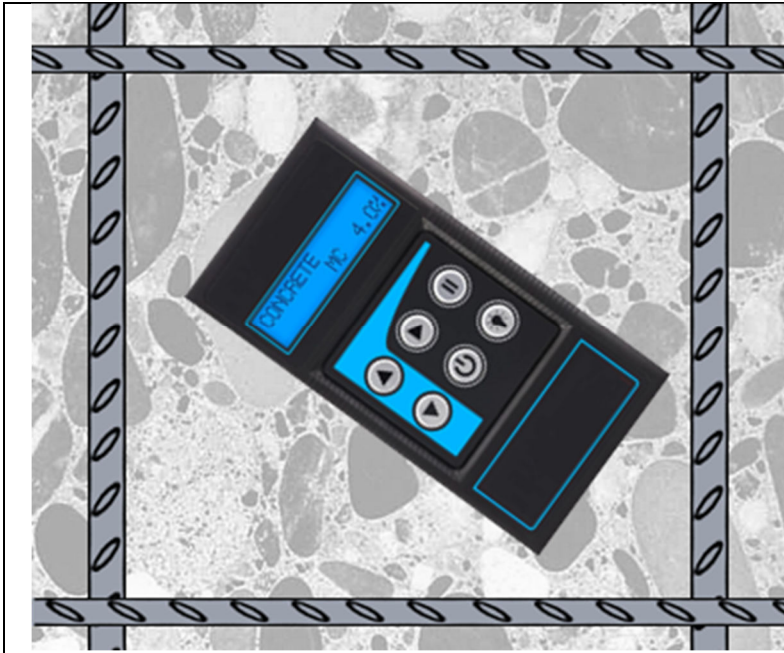


Fig. 2



Fig. 3

SUITABILITY OF IMPEDANCE SURFACE MOISTURE METER TO COMPLEMENT AIR-PERMEABILITY TESTS

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Abstract

The coefficient of air-permeability kT , measured non-destructively by the so-called "Torrent Method", has gained acceptance as a suitable durability indicator of the as-built cover concrete and has been standardized in Switzerland (Standard SIA 262/1:2013 Annex E). The standard adopted the ND electrical impedance method to control the moisture of site concrete, requiring that the latter should not exceed 5.5% for making meaningful readings of kT .

This paper presents data of moisture changes, assessed gravimetrically (H) and by ND Impedance (m) of concrete cubes dried naturally in the lab (during ≈ 3 years) and in an oven at 50°C (during ≈ 5 months). The changes in H , m and air-permeability kT were monitored regularly. Data of 17 concrete mixes, made with 9 different cement types (produced from 2 clinkers), are presented and discussed. A monotonic decrease of m and increase of kT was observed along the drying process, with reasonable continuity between natural and oven dried specimens. The results confirm that the impedance-based surface moisture meter is a suitable instrument to monitor the changes in humidity of drying concrete and an essential complement when measuring kT . The results obtained are very useful for establishing a preconditioning process prior to kT tests in the lab and offer solid ground for developing a correction factor of kT as function of m , when the latter is outside the range 4.5% - 5.5%.

Keywords: moisture, drying, air permeability, non destructive, impedance

1. INTRODUCTION

The coefficient of permeability to gases of the concrete cover has been acknowledged as a suitable and practical durability indicator [1].

It is well known that the moisture content in the concrete strongly affects the results of a gas-permeability test, due to its blocking effect on the flow of gas through the pore system of the material. To avoid this problem, laboratory samples (cast specimens or drilled cores) are preconditioned by a controlled drying process before measuring gas-permeability [2-4].

The Swiss Code 262 [5] prescribes: “The impermeability of the cover concrete shall be checked by means of permeability tests (e.g. air permeability measurements) on the structure or on core samples taken from the structure”.

Measuring the air-permeability of concrete structures on site poses the problem of the virtual impossibility of artificially preconditioning the measuring area. The tests have to be conducted on a concrete, the moisture content of which is usually unpredictable and unknown, raising doubts on the validity of the test results.

The new version (1st August 2013) of the Swiss Standard SIA 262/1 [6], which describes in Annex E how to conduct the site air-permeability test, prescribes:

1. The moisture of the concrete shall be measured by an electrical impedance-based instrument
2. The moisture content of the concrete at the point where the coefficient of air-permeability kT is to be measured should not exceed 5.5%

Preliminary results of an investigation to better understand the meaning of the surface moisture readings, based on Electrical Impedance Method and their relation with kT were presented in [7]. This paper presents new results totalling 17 mixes made with 9 binders produced from 2 different clinkers.

2. OBJECTIVE OF THE INVESTIGATION

The objective of this investigation was twofold:

- To check the suitability of Electrical Impedance to monitor the surface moisture of drying concrete
- To develop a pre-conditioning procedure to measure kT in the laboratory

3. EXPERIMENTAL

3.1 Mixes, Specimens, Curing and Storage

Each pair of mixes (w/c=0.40 and 0.65) was prepared with a different binder, covering a wide range of compositions, as described in Table 1.¹

In Table 1, the first letter of the code indicates the clinker used to produce the cements (H: Höver, Germany; M: Merone, Italy). The values in brackets indicate the content and type of mineral additions originally included in the cement (MIC). When a mineral addition was added separately as Supplementary Cementitious Material (SCM) into the concrete mix, the content and type is indicated in italics².

Two 150 mm cubes of each mix were cured in a moist room (20°C, > 95% RH) for around 3 months. The long curing period was deliberately established to ensure a high degree of hydration, so as to minimize further hydration during the drying period.

After completion of the moist curing period, one cube of each mix was exposed to natural laboratory drying (stored in a room with still air at 18-23 °C and 50-65% RH) during 3 ± 0.2 years. The companion cubes were kept in a ventilated oven at 50°C during 4 to 6 months (tests of the oven-dried cubes were performed after 24 ± 2 hour cooling in the laboratory dry room). After the tests were completed, the cubes were immediately returned to the oven.

¹ For cement M0, only the mix with w/c 0.65 was tested.

² Mixes are described with the cement code - w/c ratio (%); e.g. H0-40; M31FL-65.

Table 1. Binders used in the Concrete Mixes

Code	Brand (MIC) + SCM	EN Class
H0	Holcim Pur-5N	CEM I 52.5 N
H8M	92 % Holcim Pur-5N + 8% Silica Fume	CEM II/A-D
H22S	Holcim Ferro 4 (22% GBFS)	CEM II/B-S 42.5 R
H41S	Holcim Duo 4 (41% GBFS)	CEM III/A 42.5 N
H68S	Holcim Aqua 4 (68% GBFS)	CEM III/B 42.5 L
M0	I 52,5 R	CEM I 52.5 R
M26L	II/B-LL 32.5R (26% Limestone Filler)	CEM II/B-LL 32.5 R
M31FL	IV/A 32,5 R (27% Fly Ash + 4% LF)	CEM IV/A 32.5 R
M40FL	87% IV/A 32,5 R + 13% Fly Ash	CEM IV/B 32.5

3.2 Test Methods and Instruments

Figs. 1 and 2 show the instruments used and a sketch of the location of the testing points. At intervals, the following NDT and (Instruments) were applied on the cubes (Fig. 1):

- Mass M (10 kg/0.1 g Kern Scale)
- Moisture by impedance method m (*CMExpert*). The instrument's scale goes from 0.0 to 6.9 % [8]
- Wenner Electrical resistivity ρ (*RESI*). These results are not discussed here, as the new results confirm that ρ is not a useful indicator of concrete moisture, as already discussed in [7]
- Air-Permeability kT (*PermeaTORR*). The instrument measures values of $kT \geq 0.001 \cdot 10^{-16} \text{ m}^2$

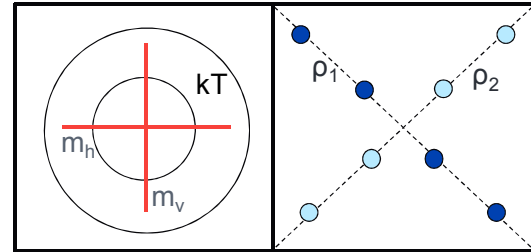
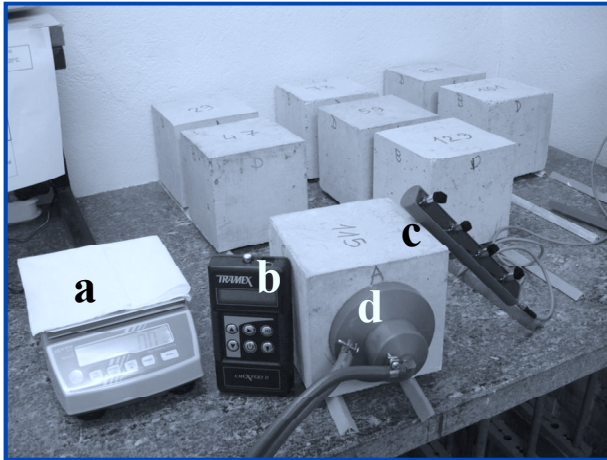


Fig. 2 - Sketch of the location of testing points

Fig. 1 - Cubes and instruments used

Reported value m is the average of 4 readings on each cube; reported value of kT is the geometric mean of both values measured on each cube. For more details, see [7].

When the 50°C oven-dried specimens had completed at least 4 months of drying, they were weighed and dried at 105 °C till constant weight, recording the mass M_{105} , and measuring kT and m . Then, the samples were submerged under water at 20°C until constant weight, recording the saturated mass M_s . This allowed converting the values of mass M of all the cubes into bulk moisture H (%) and degree of saturation S_d (-), using (1) and (2), respectively.

$$H = (M - M_{105}) / M_{105} \cdot 100 \quad (1)$$

$$S_d = (M - M_{105}) / (M_s - M_{105}) \quad (2)$$

4. TEST RESULTS AND DISCUSSION

4.1 Relation between m and H

Figs. 3 and 4 show the relation between the surface moisture m (impedance test) and the gravimetric bulk density H , see Eq. (1), for Höver and Merone mixes, respectively. The framed symbols correspond to results obtained on oven-dried cubes.

For Höver mixes, Fig. 3, the results are balancedly scattered around the equility line $m = H$, with a trend of m overestimating H for mixes with $w/c = 0.40$ (blue symbols) and underestimating it for $w/c = 0.65$ (red symbols). For values of $m \leq 3\%$, the estimate of H is quite accurate, but not for $m > 3\%$; in particular, the $w/c = 0.40$ mixes show a marked non-linear behaviour for $m > 4\%$.

For Merone mixes made with M0 (OPC) and M26L (26% limestone filler), Fig. 4, m grossly overestimates H along the whole range of humidities, whilst for binders containing fly-ash, m estimates H quite accurately.

It has to be mentioned that m measures the moisture content of a surface layer 15-20 mm thick [9], whilst H measures the bulk moisture of the whole cube. Due to the expected moisture gradient, more severe for the oven-dried cubes, the surface moisture should be lower than the average (bulk moisture). The results of Figs. 3 and 4 suggest that m is, in most cases, overestimating the true surface moisture of concrete.

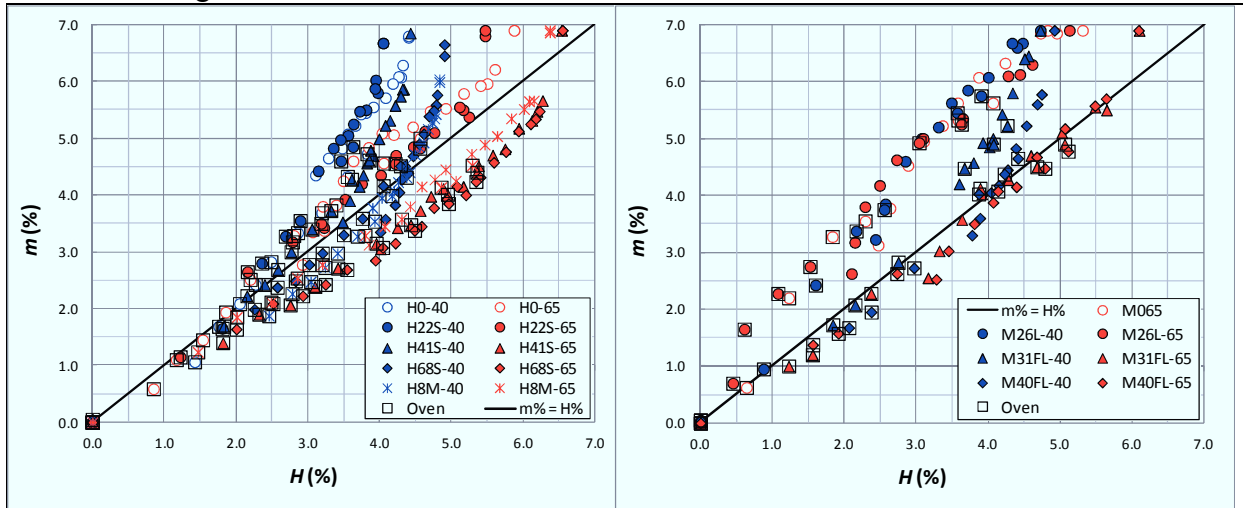


Fig. 3 - Relation between m and H (Höver)

Fig. 4 - Relation between m and H (Merone)

4.2 Relation between m and S_d

Figs. 5 and 6 show the relation between surface moisture m and bulk saturation degree S_d , see Eq. (2) for the cubes made with Höver and Merone clinkers, respectively.

All specimens' results are plotted in the charts, including those under laboratory and oven drying, the latter identified by the framed symbols. It is worth mentioning that all the cubes showed that:

- after 105°C drying to constant mass ($S_d = 0.0$) $\rightarrow m = 0.0\%$ (bottom of instrument's scale)
- after water saturation to constant mass ($S_d = 1.0$) $\rightarrow m = 6.9\%$ (top of instrument's scale)

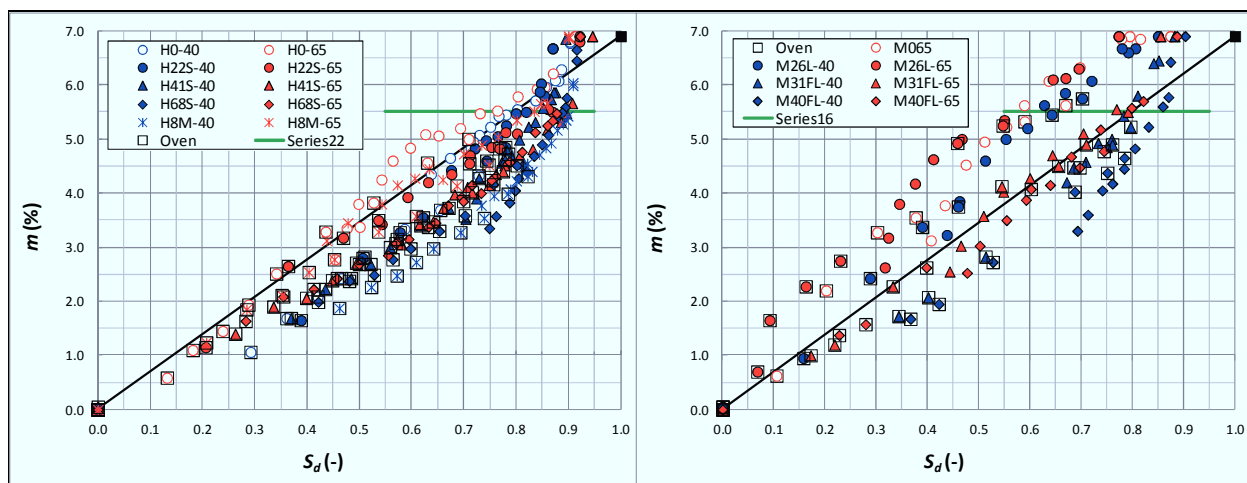


Fig. 5 - Relation between m and S_d (Höver)

Fig. 6 - Relation between m and S_d (Merone)

This situation is indicated by the solid black line (indicative only) joining the extreme black squares.

Figs. 5 and 6 show the monotonic relation existing between S_d and m along the whole drying process, with the oven-dried samples showing reasonable continuity with the lab dried.

Comparing Figs. 5 and 6, it can be concluded that the binder type, in particular the clinker type, exerts a significant influence on the S_d vs. m relationship. Indeed, for the same m values, the S_d obtained on the cubes made with Merone clinker (Fig. 6) show a larger scatter with a tendency towards lower S_d values than Höver's (Fig. 5). It can also be observed that, for the same m , concretes made with H0 and M0 (OPC) and M26L (26% limestone filler), show lower values of S_d than those containing hydraulic MIC and/or SCM.

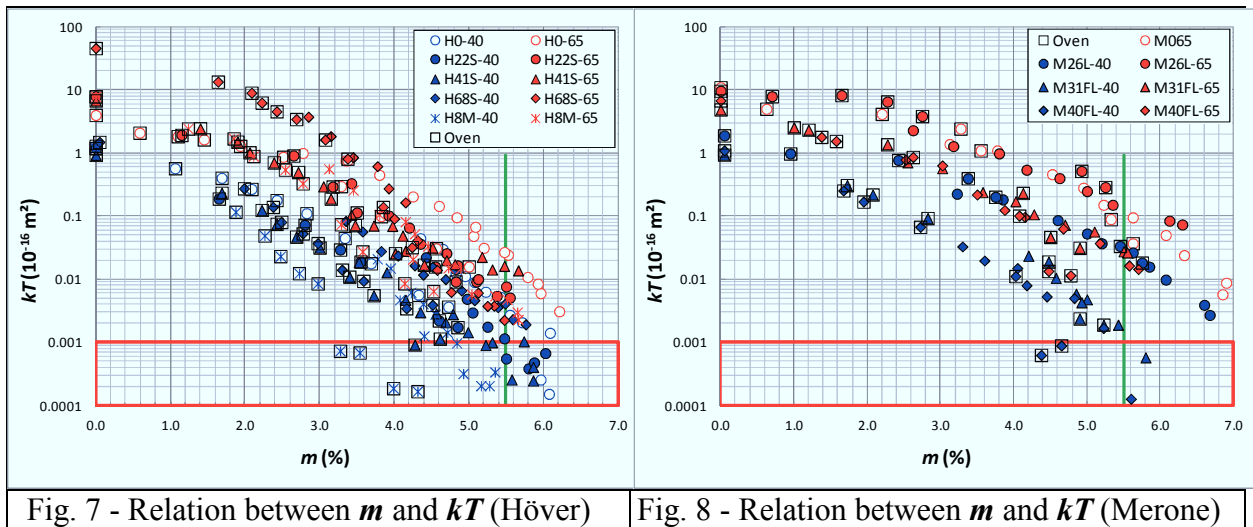
In both Figs. 5 and 6 a segment with $m = 5.5\%$ (maximum value admitted by Swiss Standard SIA 262/1 [6] for performing air-permeability test kT on site) corresponds to S_d within 0.75-0.90 for Höver samples and 0.60-0.90 for Merone samples.

4.4 Relation between kT and m

Figs. 7 and 8 show the relation between the coefficient of air-permeability kT and the surface moisture m , for Höver and Merone cubes, respectively. Results measured on cubes under both lab and oven drying are plotted, the latter indicated by the framed symbols. The values of $kT < 0.001 \cdot 10^{-16} \text{ m}^2$ are not accurate, being below the limit of sensitivity of the instrument, as indicated by the red box at the bottom of both Figs. Therefore, the values inside the box, calculated from the pressures recorded by the instrument, should be taken with caution. The limit value of $m \leq 5.5\%$, stipulated by Swiss Standard SIA 262/1 [6] for measuring kT on site, is indicated by a vertical green line in both Figs. Given the wide range of kT results, a logarithmic scale is used in Figs. 7 and 8.

There is a monotonic increase in kT as concrete gets drier, with the highest kT value corresponding to the cubes subjected to the drastic final drying at 105°C ($m = 0\%$).

At first sight, the relation $\ln(kT)$ vs. m presented in Figs. 7 and 8 show some linearity and parallelism for the different mixes, particularly for values of m within the range 1.0 - 5.5%. This opens the way for attempting a correction of kT when the m values are too low (e.g. indoors elements), to be presented in a future communication.



4.5 Drying conditions for kT laboratory tests

In [10], guidelines are given for testing kT in the laboratory, which is not covered by Swiss Standard SIA 262/1 [6] which refers exclusively to site testing. Regarding pre-conditioning of the samples, [10] specifies the following procedure: "Place the specimens in the ventilated oven at $50^{\circ} \pm 2^{\circ} \text{C}$, making sure that hot air can circulate freely over the faces to be tested (a free distance of at least 20 mm should be left between the test faces of adjacent specimens and/or the oven's walls and floor. After 3 days, remove the samples from the oven and let them cool down in a laboratory room (relatively dry) at 20 to 23°C for 6 ± 2 hours.

Apply the Surface Moisture Meter on the surfaces where kT is to be measured, making 2 readings at 90° per test area, and check that their average is within the range 4.0 - 5.5%. Under normal circumstances, 3 days in the oven should suffice to reduce the surface moisture to the required level. If not, repeat the drying and cooling procedure until the moisture falls within the specified range."

This criterion has been applied to the data recorded in this investigation, with the result shown in Fig. 9.

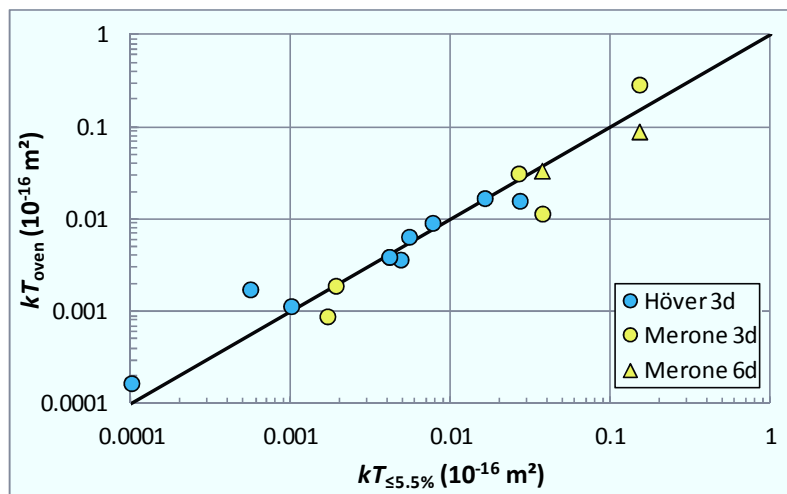


Fig. 9 - Relation between oven-dried (3 or 6 d.) and lab-dried (until $m \leq 5.5\%$) kT values

Fig. 9 shows the kT values obtained for the 17 mixes reported, in abscissas for laboratory drying until $m \leq 5.5\%$ and in ordinates after 3 days in the oven at 50°C to reach a surface moisture $4.0\% \leq m \leq 5.5\%$; if not achieved, the value obtained after 6 days in the oven was taken. It has to be mentioned that, in the case of Mix H0-40, after 3 days of oven-drying, the moisture dropped already to 3.8% . Only for mixes M0-65 and M26L-40, was it necessary to dry the specimens 6 days to reach $m \leq 5.5\%$, indicated by triangles in Fig. 9.

Fig. 9 shows that the criterion works well in that the kT values obtained according to the oven-drying procedure prescribed in [10] leads to very similar values to those obtained in lab-drying until reaching $m \leq 5.5\%$.

Fig. 10 shows the kT values obtained on the 17 mixes tested under: lab-drying till $m \leq 5.5\%$ (blue bars); oven-drying at 50°C till $m \leq 5.5\%$ (yellow bars); oven-drying at 105°C till constant mass (red bars).

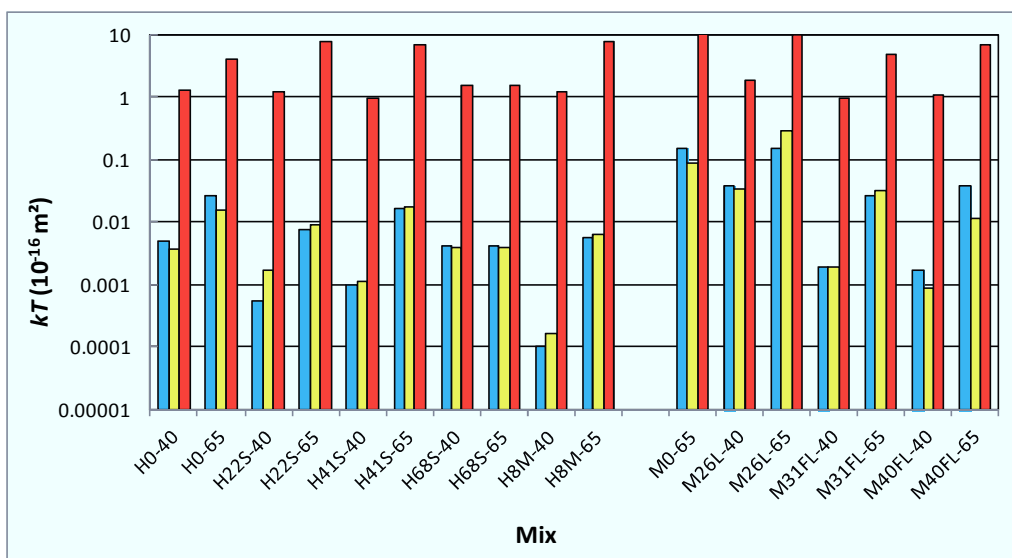


Fig. 10 - kT values of 17 mixes after three different drying regimes

The results presented in Fig. 10 show the inconvenience of drying the samples at 105°C (as applied in [11,12]), because the kT values obtained after such drastic drying are several orders of magnitude higher than those expected for surface moisture $4.0\% \leq m \leq 5.5\%$ and, therefore, not representative of normal field conditions. Moreover, the difference between kT of mixes H8M-40 and M0-65, which is three orders of magnitude for lab-drying and 50°C oven-drying, is reduced to just one order of magnitude after 105°C oven-drying.

5. CONCLUSIONS

- The impedance method is a good NDT to follow the effect of drying on the surface moisture of concrete m ; 105°C oven-dried specimens have $m = 0.0\%$ (bottom of scale) and water saturated samples have $m = 6.9\%$ (top of scale)
- For each mix, m relates well with the bulk moisture H and saturation degree S_d , with continuity between laboratory and oven-dried specimens, although the relations vary with the type of mix and binder.
- The impedance method is suitable to monitor the effect of surface moisture on air permeability coefficient kT test results.

- d) The *PermeaTORR* and the *CMExpert* instruments followed well the evolution of kT and m under drying conditions, during 3 years (good stability and repeatability).
- e) The limit established in the Swiss Standards for surface moisture ($m \leq 5.5\%$) seems adequate and corresponds, in terms of measured kT , to 3 days drying at 50°C in the oven used in this investigation.
- f) This is acceptable for new structures (28-91 days of age), to which the Standard applies (where m is typically within the range 4.5%-5.5%), but not to old structures where m can be considerably lower.
- g) The 'parallelism' of the relation $\ln(kT)$ vs m for the different mixes opens a way to correct the measured values of kT when the moisture meter reading m is out of the usual range 4.5% - 5.5%
- h) For lab applications, oven-drying at 50°C and checking that the surface moisture m is within 4.0-5.5%, may be a robust and realistic conditioning procedure for lab specimens to be tested for kT . On the contrary, strong drying at 105°C is not recommended.

ACKNOWLEDGMENT

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Effect of surface moisture on air-permeability kT and its correction

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Abstract It is a well-known fact that moisture in the pores hinders the flow of gas through them, thus having a strong effect on the gas-permeability of concrete. Contrary to laboratory tests, where specimens can be preconditioned by drying, site air-permeability tests are normally conducted under the natural moisture conditions prevailing at the moment of the measurement. Swiss Standard SIA262/1-E: 2019 prescribes that the site air-permeability test (double vacuum cell or Torrent method) is applicable to measure the air-permeability coefficient, kT , only

when the surface moisture content m does not exceed 5.5%, m measured with an electrical impedance-based instrument. This paper analyses 50 sets of parallel data of kT and m , recorded during different drying processes, originated from five independent investigations. The analysis confirms that a relation of the type $kT = kT_0 \cdot e^{-\delta \cdot m}$ can be fitted to the large majority of the cases ($\bar{R} = 0.95$), with δ falling within 1.0–2.0 in 84% of the 50 cases analysed, with a median value of 1.45. This analysis allows the authors to propose a practical method to correct the effect of m on kT , the robustness of which is verified by a sensitive analysis. The correction is of little practical relevance for surface moistures between 4.5% and 5.5%. It is expected that this correction may be included in future versions of standards.

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1 Introduction

A non-destructive test method for measuring the coefficient of permeability of concrete to air (kT), was developed using a double vacuum cell in the early 90's [1], which gradually attracted the interest of researchers and practitioners worldwide, Japan being today the country where the test method is most intensively



used. In 2003, the test method was originally introduced, as accepted test method, into the Swiss Standards, with updates in 2013 and, more recently, in 2019 [2].

kT is governed, to a large extent, by the pore structure of the concrete tested (size and volume of pores, especially of capillary pores) [3–5]. By varying the mix composition and curing conditions, a wide range of kT values can be obtained spanning 5–6 orders of magnitude (from $< 0.001 \times 10^{-16} \text{ m}^2$ to $> 100 \times 10^{-16} \text{ m}^2$) [6]. This is a positive aspect because aggressive agents such as CO_2 , Cl^- and SO_4^{2-} penetrate through the concrete surface by different mechanisms (permeation, capillary suction, diffusion) at rates that are also function of the pore structure of the material. Hence, good correlations have been found between kT and other transport tests' parameters or durability indicators (e.g., water sorptivity, water penetration under pressure, O_2 diffusion, carbonation rate, Cl^- diffusion, and migration) [7–10].

However, kT is also strongly influenced by the degree of saturation of the pore system. Indeed, a concrete with large volume and size of capillary pores (intrinsically highly permeable) would show, under high saturation degree conditions, a rather low permeability as the water in the pores would block the flow of air through them. This effect has been investigated by different researchers [11–14] who tend to agree that the effect of moisture would reduce the value of gas-permeability by three orders of magnitude when tested oven-dried at $105 \text{ }^\circ\text{C}$ and near full saturation. This effect has prompted some researchers to use gas-permeability as an indirect indicator of moisture in concrete [15], with even the design of an embedded sensor to monitor moisture changes, based on this principle [16].

In the laboratory, the effect of moisture is not a serious problem because the specimens can be preconditioned to control the moisture content. For example, storage during some weeks in a dry room or by oven-drying (typically at temperatures $\approx 50 \text{ }^\circ\text{C}$) for periods of about 3 to 7 days is a common procedure for measuring the gas permeability of concrete in the laboratory, see for instance [17–19].

The problem becomes more challenging when testing air-permeability on site, as no practical way of preconditioning the testing areas of structural members has been yet developed. Therefore, the test has to be performed at the moisture conditions

prevailing at the moment of the measurement, obviously trying to avoid conditions of high moisture (during or immediately after the end of curing periods or after wetting by rain, splash or spray of water). Even after avoiding the high moisture condition, changes in moisture continuously affect the measured air-permeability [20]. It should be reminded that kT is measured through the so called *Covercrete*, i.e., the surface layers of a concrete element/specimen, with properties essentially different from those of the bulk concrete. Therefore, what matters is the moisture content of those few centimetres affected by the test, which are, in turn, strongly affected by the fluctuating environmental conditions surrounding the element.

The objective of this paper is to analyse the relation between surface moisture m and air-permeability kT , of concretes left drying naturally and in an oven at $50 \text{ }^\circ\text{C}$, from 5 different data sources. The aim of the analysis is to find a way to correct the effect of m on the measured kT of concrete in order to evaluate the *Covercrete* quality, which is a crucial factor for the durability of concrete structures.

2 Background

2.1 Early attempts to compensate the effect of moisture on kT

In an early investigation to assess the quality of the *Covercrete* [21], the following was stated (translation from German): “It was clear, from the very beginning of the investigation that the moisture content (saturation degree) of concrete is a very important factor in the site measurement of the quality of the cover concrete”. The investigation was conducted at the laboratories of “Holderbank” Management & Consulting Ltd. (later Holcim Technologies Ltd.), under a grant of the Swiss Federal Highways Administration.

Based on an excellent review of the topic [22], different techniques available at the time (90's) were investigated in [21], namely:

- (a) A sensor to measure the temperature and relative humidity (RH) of the concrete inside a drilled hole, based on the changes in the capacitance of a “Kondensator” (Vaisala)



- (b) A contact instrument to measure the surface moisture by means of the complex magnetic dielectric constant (James H2O meter)
- (c) A contact instrument to measure the electrical resistivity ρ of the *Covercrete* by the 4-electrodes Wenner method (RESI)

Instrument (a) was found impractical, because it required drilling $\text{Ø}13 \times 40$ mm holes in the structure (often objected by the owners) and for the relatively long time (30 min) required for the reading to stabilize. Instrument (b) simply did not perform according to the specifications and was returned to the supplier.

Therefore, the investigation focused on instrument (c), which looked the most promising. In a second part [23] of the same investigation [21], a criterion to compensate the effect of moisture by parallel measurements of kT and ρ was developed, which was short-lived [24]. Indeed, at the time of the investigation, virtually all concretes in Switzerland were prepared with OPC. With the advent of supplementary cementitious materials (SCMs), such as fly ash and silica fume, that exert a huge impact on the electrical resistivity, the approach lost validity and was gradually abandoned.

2.2 Recent attempts to compensate the effect of moisture on kT

An approach to correct the kT values for the moisture content of concrete was developed in Czech Republic [25]. Concrete slabs ($300 \times 300 \times 100$ mm) of 25 MPa (cube strength) class concrete were cast, moist cured for $28 + 2$ days and then stored in a dry room (23°C , 48% RH), monitoring the effect of drying on kT . Later, the samples were oven-dried at 50°C and finally at 105°C . The moisture content, w , was measured with a KAKASO capacitive humidity meter, that was calibrated against bulk gravimetric moisture content. Based on 153 test results, a relation between kT and w of the following form was proposed [25]:

$$kT = kT_0 \cdot e^{-\alpha \cdot w} \quad (1)$$

For the particular mix investigated and the moisture indication of the device used, it was found that $kT_0 = 5.25 \times 10^{-16} \text{ m}^2$ and $\alpha = 0.862$.

An investigation conducted at Empa laboratory in Switzerland [26], to be described in Sect. 3.2, demonstrated the suitability of an instrument, based on measuring the changes in electrical impedance, to measure the surface moisture of concrete. The instrument was the analogic “Concrete Encounter Moisture Meter”, later upgraded into the digital “CMEXpert II”, both manufactured by Tramex in the Republic of Ireland. The suitability of this kind of instrument to monitor the changes in moisture of concrete specimens, dried both in a dry room and in an oven at 50°C , was confirmed by independent researches [12, 13]. Furthermore, Kurashige et al. [27] suggested the correction of kT values with m measured by the Wenner method or impedance instrument although they did not give quantitative discussion.

In a round robin test designed to check the reproducibility of the air-permeability kT test, applied by five different Swiss laboratories on site on a bridge [24], two of them were unable to measure the electrical resistivity, but Empa managed to measure the surface moisture with the impedance instrument.

Since then, the electrical impedance has been adopted in Switzerland as a suitable method to assess the surface moisture of the concrete. Swiss Standard 262/1:2019 [2] prescribes that kT can be measured on site, provided that the moisture content, as indicated by the electrical impedance instrument, does not exceed 5.5%.

3 Data sources

The data used for the analysis of the relation between m and kT of drying concrete come from five different independent sources, as described below. The one described in Sect. 3.1 was specifically designed to investigate the effect of drying on m and kT , whilst the main objective of the other four was different, although the methodology applied provided, as side-product, parallel data of m and kT of drying concretes.

It is important to mention that during the drying process, two phenomena take place simultaneously, a decrease of the permeability due to further hydration of young concrete and an increase of permeability due to the freeing of water-filled pores due to desiccation. To discuss the second phenomenon in this paper, the data obtained from young concrete was excluded in the later analysis. Furthermore, drying-induced



microcracking can significantly increase the permeability of concrete under drying process [29]. Basically, clear impact was not observed in this study using relatively massive specimens under slow drying process. But, in some cases, sudden increases in the measured permeability were caused by drying-induced microcracking because of thin cover concrete. These exceptions have been excluded as mentioned in Sect. 3.3 to focus on the permeability increase due to moisture decrease. Furthermore, carbonation effect during drying process might be included because it could change pore structure of concrete [29].

3.1 Specifically oriented research

The declared objective of the research described in [12, 13] was to check the suitability of the electrical impedance instrument to monitor the surface moisture of drying concrete and to develop a pre-conditioning procedure to measure kT in the laboratory.

Parallel data of m and kT during drying were obtained on 150 mm cubes of concretes with water-to-cement (w/c) ratios of 0.40 and 0.65, made with 9 different binder types, described in Table 1. The cubes were supplied by Holcim Technologies Ltd. and cured, stored and dried at SUPSI laboratories, where they were tested by Materials Advanced Services Sagl, all in Switzerland.

The first letter of the code indicates the clinker used to produce the cements (H: Höver, Germany; M: Merone, Italy). The values in parentheses in Table 1 indicate the content and type of mineral additions originally included in the cement (MIC). When a mineral addition was added separately as Supplementary Cementitious Material (SCM) into the concrete mix, the content and type are indicated in italics. Each

concrete mix is identified by the binder code followed by the w/c ratio in percent, e.g. H8M-40 or M26L-65. Two cubes of each mix were cured under water at 20 °C for around 3 months to ensure a high degree of hydration, so as to minimize further hydration during the drying period.

After the moist curing period, one cube of each mix was exposed to natural laboratory drying (stored in a room with still air at 20 °C and 50–65% RH). The companion cube was placed in a ventilated oven at 50 °C (tests of the oven-dried cubes were performed after 24 ± 2 h cooling in the dry room). After the tests were being completed (over 3 years for the lab stored and over 4 months for the oven-dried specimens), the cubes were immediately returned to the dry room or oven, respectively. At intervals, m and kT were monitored utilizing Tramex *CMEXpert II* and air-permeability kT tester (*PermeaTORR*), respectively (more details in [12, 13]).

Two readings of m were made on each of two opposite surfaces; the reported value of m is the average of the 4 readings on each cube. One reading of kT was performed on each opposite surface; the reported value of kT is the geometric mean of both values for each cube. Figure 1 shows the changes in kT with storage time (square root scale) in the dry room for 6 of the 17 mixes investigated. The measured kT values gradually increased with time due to water evaporation. The correlation between kT and m is reported in Sect. 4.

When the 50 °C oven-dried specimens had completed at least 100 days of drying, they were dried at 105 °C till constant weight, measuring kT and m . Invariably, the m value of the specimens dried at 105 °C was close to 0% (see Fig. 6).

Table 1 Binders used in the concrete mixes

Code	Brand (MIC) + <i>SCM</i>	EN 197 Class
H0	Holcim Pur-5 N	CEM I 52.5 N
H8M	92% Holcim Pur-5 N + 8% <i>Silica Fume</i>	CEM II/A-D
H22S	Holcim Ferro 4 (22% GBFS)	CEM II/B-S 42.5R
H41S	Holcim Duo 4 (41% GBFS)	CEM III/A 42.5 N
H68S	Holcim Aqua 4 (68% GBFS)	CEM III/B 42.5L
M0	I 52,5R	CEM I 52.5R
M26L	II/B-LL 32.5R (26% Limestone Filler)	CEM II/B-LL 32.5R
M31FL	IV/A 32,5R (27% Fly Ash + 4% Limestone Filler)	CEM IV/A 32.5R
M40FL	87% IV/A 32,5R + 13% <i>Fly Ash</i>	CEM IV/B 32.5 N



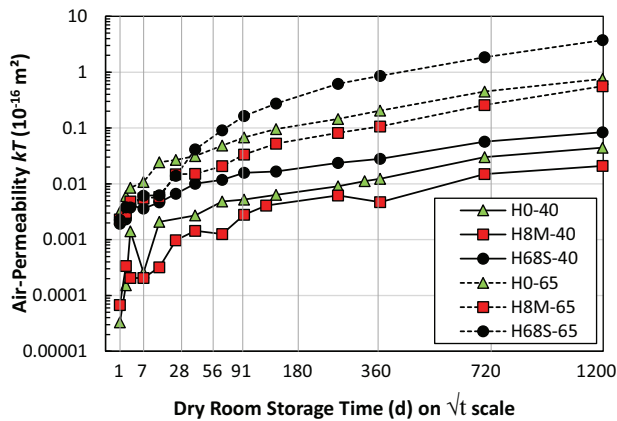


Fig. 1 Changes in kT of cubes stored at an age of ≈ 3 months in a dry room (20 °C, 50–65% RH)

3.2 Research at Empa

The data correspond to a very comprehensive research, conducted at Empa laboratories in Switzerland, in which 200 mm cubes, prepared with 6 concrete mixes with the compositions indicated in Table 2, were kept at 20 °C in rooms at different RH (35, 70, and 90%) [26, 30]. The cubes were cured in a moist room for 48 h, moment at which they were demoulded and sealed along four sides, leaving just two opposite faces open to the environment. Immediately thereafter, two cubes of each mix were stored in the corresponding room; since this research focuses on the effect of drying, only the data obtained on the cubes stored at 35% RH will be analysed. The results at 70 and 90% RH were excluded from the analysis because the changes in moisture contents and kT were too small to calculate slopes accurately.

At ages of 7, 14, 28, 56, 91, 140, 210, and 365 days, the surface moisture m (*Concrete Encounter Moisture Meter*) and the coefficient of air-permeability kT (*Torrent Permeability Tester*) were measured on 2

cubes of each mix. The change of kT with age at 35% RH is shown in Fig. 2.

Contrary to Fig. 1, Fig. 2 shows that, at ages up to 28 days, all mixes excluded M3 show systematically some reduction in kT , attributable to continued hydration, due to the moisture still contained in the young cubes. Therefore, to study the effect of drying, only the data at 28 days and later ages will be considered.

3.3 Research at Ehime University

The declared main objective of this investigation [31] was to study the influence of bleeding on the modification of the pore structure of concrete as evidenced by its air permeability. Here, the moisture content and the possible occurrence of carbonation-induced corrosion formation in concrete column specimens with embedded steel were investigated. For this, full scale columns (0.3 × 0.3 × 1.5 m, cover depth = 10 mm) were cast from the top with five concrete mixes, the main characteristics of which are shown in Table 3 [31, 32]. Some mixes included Cu slag as fine aggregate and fly ash as binder. The compressive strength of the mixes ranged between 33 and 38 MPa.

Before accelerated carbonation-induced corrosion tests, the columns were stored from the very beginning in a room with 20 °C and 60% RH, where they were permanently kept. The surface moisture content m (*CMEXpert II* instrument) and the air-permeability kT (*PermeaTORR* instrument) were measured on the front face, at three heights (250, 750, and 1250 mm) from the bottom of the columns and at different ages (up to 190 or 540 days, depending on the mix).

Some specimens showed strange behaviour, like a jump in kT after 284 days of drying for Mix FACUS60 (see Fig. 3). One possible explanation could be the

Table 2 Main characteristics of the mixes tested at Empa

Mix		M1	M2	M3	M4	M5	M6
Cement type*		OPC	OPC	OPC	LFC	OPC	OPC
w/c	–	0.35	0.483	0.40	0.483	0.622	0.483
Cement Content	kg/m ³	380	300	325	300	275	300
Air Content	%	2.8	1.7	3.2	1.5	2.0	5.2
28d. Cube Strength	MPa	55.3	47.4	48.1	44.4	35.0	31.2

*The OPC corresponds to EN 197 class CEM I 42.5 and Limestone Filler Cement (LFC) to CEM II A-L 32.5

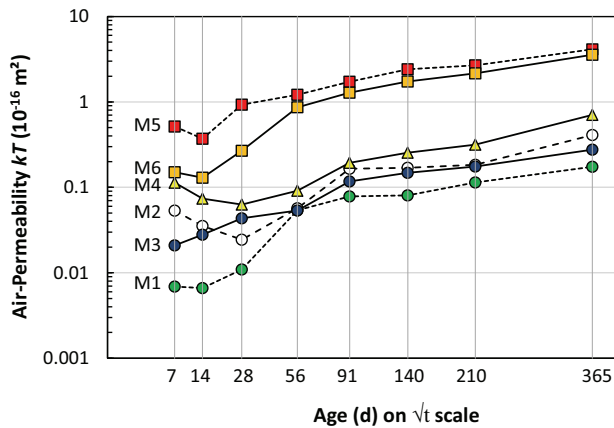


Fig. 2 Changes in kT of cubes stored at an age of 48 h in a dry room (20 °C, 35% RH)

effect of drying-induced microcracks [28], which were promoted by thin cover concrete (10 mm). Therefore, such abnormal results of this investigation had to be excluded.

3.4 Research at Hiroshima University

This research aimed at developing a novel measurement approach to evaluate the quality of Covercrete using the water intentional spraying test [33, 34]. For comparison purposes, a set of prisms of conventional concretes was cast in the laboratory and seal-cured at normal temperature.

The prisms (300 × 200 × 800 mm) were prepared in the laboratory with six concrete mixes (see Table 4), keeping them sealed during 1, 5, 7 or 28 days. Thereafter, the lateral faces of the prisms were sealed with aluminum tape, leaving just the two 800 × 300 mm opposite vertical surfaces open to an environment with average conditions of 20.7 °C and 62.6% RH.

The prisms were allowed to dry naturally, monitoring the changes in surface moisture m (*CMExpert*

Table 3 Main characteristics of the mixes tested at Ehime University

Mix		OPC	CUS30	CUS60	FACUS30	FACUS60
w/b	(-)	0.60	0.60	0.60	0.525	0.525
OPC Content	(kg/m ³)	275	275	275	251	251
Fly Ash Content	(kg/m ³)	-	-	-	38	63
Cu Slag in Sand	(wt%)	-	36.6	66.9	37.7	69.6

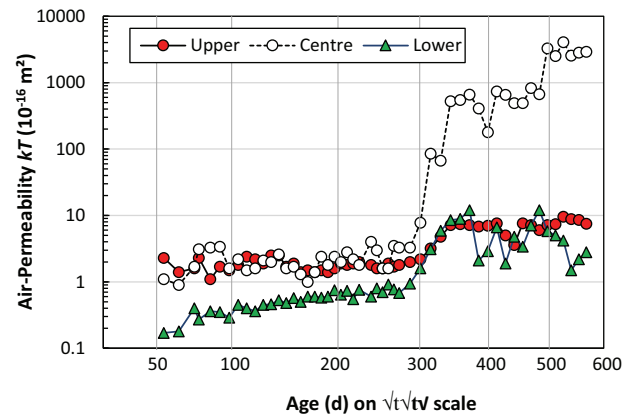


Fig. 3 Changes in kT for mix FACUS60 concrete column with embedded steel

Table 4 Main characteristics of the concrete mixes used in Hiroshima Univ. research

Mix code		Laboratory prisms					
		N35	N45	N50	N55	B25	B45
w/c	(-)	0.35	0.45	0.50	0.55	0.25	0.45
OPC	(kg/m ³)	486	378	340	309	-	-
BFSC*	(kg/m ³)	-	-	-	-	680	378

*BFSC means blast-furnace slag cement

II) and air-permeability kT (*PermeaTORR*) at 4 test locations on each prism.

Figure 4 shows the evolution of kT of the prisms (identified by the Mix Code followed by the sealed curing length in days). Similar trends as those shown in Fig. 2 were observed at ages below 28 days, presumably for the same reasons discussed in Sect. 3.2. Hence, the analysis will be performed only with data at ages ≥ 28 days.



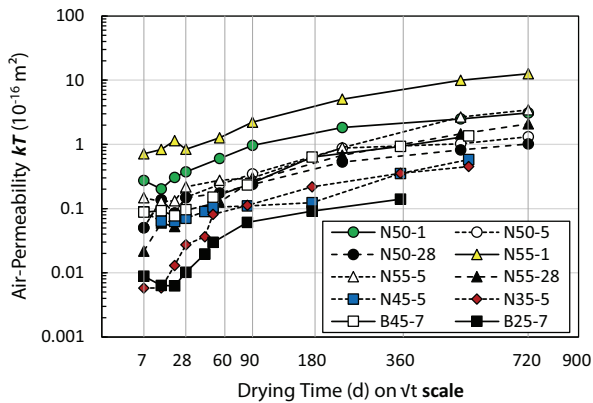


Fig. 4 Changes in kT for laboratory prisms ($\sim 20\text{ }^\circ\text{C}$, $\sim 60\%$ RH)

3.5 Research at Gunma prefecture

The aim of this study was to investigate the effect of drying on site measurements of transport properties of Covercrete [20]. For this, two concrete box culverts: N-box and B-box types (35 and 12 m long, respectively), were constructed in Gunma Prefecture, Japan, as parts of new highway structures. The N-box was cast with concrete mix N and the B-box with mix B (see data in Table 5), both supplied by a ready-mixed concrete company and cast on site, using boom concrete pumps. After removing the formwork at an age of approximately 7 days, the surfaces were sealed using plastic films for three months. The interior walls were targeted for measurements in this study. The average temperature and RH during a period of three years, recorded at the nearest meteorological station, were $16.0\text{ }^\circ\text{C}$ and 62.1% , respectively.

Simultaneously, three large-scale reinforced concrete mock-up panels ($1.5 \times 1.5\text{ m}$), with thickness of 0.6 m and 0.4 m , for the N mix and B mix, respectively, were cast with each mix. After stripping them at 1 day, three curing conditions were imposed to the panels, consisting in leaving them exposed without any protection (panels N-1d and B-1d), seal-curing

them for 5 or 7 days (panels N-5d and B-7d) and for 3 months (panels N-3 m and B-3 m). After curing, the narrow sides of the panels were continuously sealed, leaving the large surfaces ($1.5 \times 1.5\text{ m}$) exposed to the same environment as the box culverts, protected from the rain. More details can be found in [20]. Measurement of surface moisture m (CMEXpert II) and air-permeability kT (PermeaTORR) were performed (among other tests not discussed here), after 1.3, 2.6, 7.4, 13, 27, 37, 38, and 39 months of drying. The tests were conducted at mid-height of the $1.5 \times 1.5\text{ m}$ panels and at 1 m of height on the inner walls of the box culverts.

Abnormal results were observed during the second date of test (2.6 months of drying), systematically in all elements [20], as can be seen in Fig. 5 for just 4 elements (larger white symbols). This abnormality was attributed to that series of tests being performed by a different operator than the rest. Therefore, the results at 2.6 months were excluded from the analysis.

4 Results and discussion

4.1 Relation between surface moisture m and air-permeability kT

Figure 6 shows the relation between kT and m for the mixes investigated in the research described in Sect. 3.1, prepared with clinker M (similar results were reported for clinker H) [12, 13]. The values within the red box are below the sensitivity limit of the instrument ($< 0.001 \times 10^{-16}\text{ m}^2$). The points corresponding to oven-dried specimens are differentiated by framing them within a box.

Figure 6 shows that there is a monotonic increase in kT as concrete gets drier, with the highest kT value corresponding to the cubes subjected to the drastic final drying at $105\text{ }^\circ\text{C}$ ($m \approx 0\%$). The data for each mix follow a quasi-linear relation between $\ln(kT)$ and

Table 5 Main characteristics of the concrete mixes used in Gunma Prefecture research

Mix	Cement		w/c	25 mm Aggregate	Sand	AEA + WR	Slump	$f'_{c_{cyl}} 28d$
	Type	kg/m^3						
N	OPC	295	0.550	1845	44	$\approx 1\%$	120	31.9
B	BFSC	303	0.525	1837	43		150	34.4



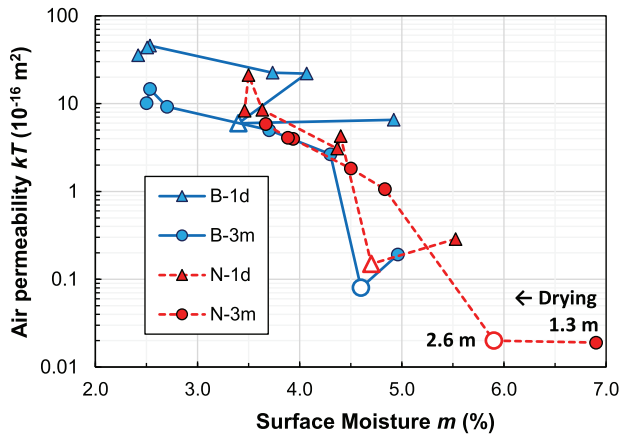


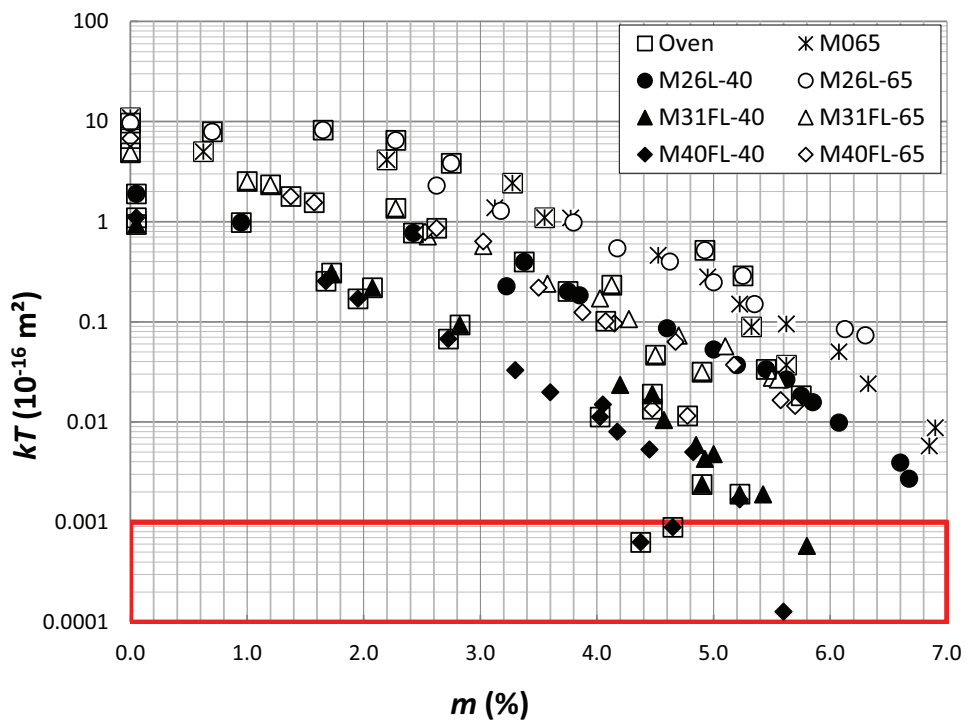
Fig. 5 Relation kT vs m , showing abnormal data for tests at 2.6 months (larger white symbols)

m , particularly for values of m within the range 1.0–6.0%. Moreover, the lines look quite parallel to each other for the different mixes.

Linear regressions between $\ln(kT)$ and m were fit to the test results of the 17 mixes, of the same mathematical form as Eq. 1, but now with m being the surface moisture indication of CMEXpert II instrument:

$$kT = kT_0 \cdot e^{-\delta \cdot m} \tag{2}$$

Fig. 6 Relation between kT and m for concretes made with M clinker



with m expressed in %; only the data with $1.0\% \leq m \leq 6.0\%$ and with $kT \geq 0.001 \times 10^{-16} \text{ m}^2$ were considered for the regression analysis, which included results obtained on both the room-dried and oven-dried specimens. Table 6 (top section) shows the values of exponent δ and correlation coefficients R , obtained from the regression analysis, for each mix. The mean correlation coefficient was $R = 0.96$, with extreme values of 0.87 and 0.99.

The data in Table 6, for this research (top section), shows that, despite the wide range of binders and w/c ratios used to prepare the concrete mixes, exponent δ remains within a limited range of 1.00–1.65 for 16 out of the 17 mixes investigated, with an average of $\delta = 1.36$ for all 17 mixes.

4.2 Validation of the relation kT vs m

The approach presented in Sect. 4.1, based on the data described in Sect. 3.1, are validated in this Section against the data from the independent sources described in Sects. 3.1, 3.2, 3.3, 3.4, 3.5. Table 6 presents the results of fitting Eq. 2 to the data recorded in those investigations.

In Table 6, δ_{28^+} means that the slope and the correlation coefficient R were computed on the kT and m data at ages ≥ 28 days. Only data where the



Table 6 Results of fitting Eq. 2 to the data recorded in the researches described in Sects. 3.1, 3.2, 3.3, 3.4, 3.5

Research: Holcim + SUPSI + MAS (Sect. 3.1)											
Binder	H0	H8M	H22S	H41S	H68S	M0	M26L	M31FL	M40FL		Mean
w/c	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40		
δ	1.17	1.20	1.29	1.59	1.16	–	1.10	1.39	1.35		
R	0.95	0.87	0.91	0.98	0.91	–	0.99	0.97	0.99		
w/c	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65		
δ	1.19	1.62	1.54	1.33	2.51	1.27	1.01	1.07	1.25		1.36
R	0.94	0.95	0.97	0.96	0.98	0.97	0.98	0.98	0.95		0.96
Research: Empa (Sect. 3.2)											
Mix	M1	M2	M3	M4	M5	M6					Mean
δ_{28^+}	1.41	1.81	1.28	1.50	1.07	1.61					1.45
R	0.87	0.95	0.95	0.96	0.99	0.99					0.95
Research: Ehime Univ. (Sect. 3.3)											
Mix	OPC	OPC	CUS30	CUS30	CUS60	CUS60	FACUS30	FACUS30	FACUS30		Mean
Point	U	C	L	U	C	U	U	C	L		
δ_{28^+}	1.33	1.80	1.87	1.10	1.19	1.19	2.32	2.32	2.16		1.70
R	0.96	0.87	0.87	0.88	0.84	0.85	0.96	0.94	0.94	<i>6 with R < 0.80</i>	0.90
Research: Hiroshima Univ. (Sect. 3.4): Laboratory Prisms											
Mix	N35	N45	N50	N50	N50	N55	N55	N55	B25	B45	Mean
Cure (d)	5	5	1	5	28	1	5	28	7	7	
δ_{28^+}	1.70	1.64	1.04	1.14	1.11	1.51	2.22	2.69	1.61	1.63	1.63
R	0.96	0.92	0.99	0.97	0.99	0.94	0.96	0.91	0.99	0.98	0.96
Research: Gunma Prefecture (Sect. 3.5): Mock-up Panels and Box Culverts											
Panel	N	N	N	B	B	B	Box Culvert	N	B		Mean
Cure	1d	5d	3 m	1d	3 m	3 m	Cure	3m	3 m		
δ_{28^+}	1.78	1.76	1.78	0.66	1.59	1.41	δ_{28^+}	2.10	1.74		1.60
R	0.96	0.98	1.00	0.94	0.96	0.92	R	0.95	0.96		0.96

correlation coefficient $R \geq 0.80$ are included in Table 6 and in the subsequent analysis (non-compliant number of cases are indicated in italics in Table 6). Only 6 out of a total of 56 cases presented correlation coefficients below 0.80 and were not included in the analysis.

Figure 7 presents the histogram of δ values obtained from all investigations (Table 6), comprising 50 cases. It can be seen that the statistical distribution is positively skewed with a central value that can be assumed equal to the median $\delta = 1.45$; $(25 + 17)/50 = 84\%$ of the δ values fall within the range 1.0–2.0. The average value of R for the 50 valid cases is $R = 0.95$.

4.3 Proposal for moisture correction

Based on the results presented in Sects. 4.1. and 4.2, a single correction equation is proposed, using the median δ value of 1.45 or, from Eq. 2, where kT_m is the air-permeability value measured under surface moisture m :

$$kT_m = kT_0 \cdot e^{-1.45m} \quad (3)$$

The value kT_0 corresponds to the extrapolation of Eq. 3, valid for $1.0\% \leq m \leq 6.0\%$, to $m = 0\%$, giving an unrepresentatively high reference value. Therefore, it is proposed to take as reference the value kT_5 , corresponding to a moisture $m = 5.0\%$, which is a



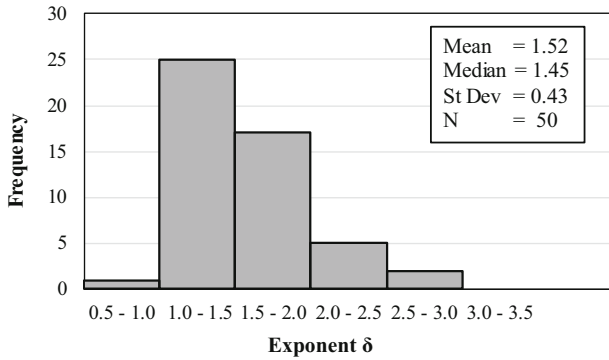


Fig. 7 Histogram of values of exponent δ found in all five reported investigations

typical value in concrete structures at the ages of 1–3 months. From Eq. 3 we can write:

$$kT_5 = kT_0 \cdot e^{-1.45 \cdot 5.0} \quad (4)$$

Dividing Eq. 4 by Eq. 3 and introducing a correction factor F_5 to the value kT_m measured at moisture m :

$$kT_5 = F_5 \cdot kT_m \quad (5)$$

with

$$F_5 = e^{1.45(m-5.0)} \quad \text{valid for } 1.0\% \leq m \leq 6.0\% \quad (6)$$

The approach is shown graphically in Fig. 8, that presents lines relating kT_m and kT_5 , for different surface moistures m . An example is shown, by which a kT_m value of $1.0 \times 10^{-16} \text{ m}^2$ has been measured under a surface moisture $m = 3.8\%$ which, applying Eqs. 5 and 6, yields a reference kT_5 value of $0.18 \times 10^{-16} \text{ m}^2$.

From Fig. 8 it can be seen that, for m values between 4.5% and 5.5% (thin dotted lines), the measured kT_m values differ from kT_5 by a factor of ≈ 0.5 and 2.0, respectively, which is not truly significant, given that kT varies over 5–6 orders of magnitude.

Equations 5 and 6 assume that δ is constant and equal to the median value found $\delta = 1.45$. As discussed in Sect. 5 (Fig. 7), 84% of the cases showed values of δ between 1.0 and 2.0. A sensitivity analysis was performed, evaluating the error if δ had the extreme values 1.0 or 2.0, instead of 1.45. Figure 9 plots the F_5 ratios (always maximum/minimum) as function of m . The F_5 ratios are: $F_5(\delta = 1.0)/F_5(\delta = 1.45)$ and $F_5(\delta = 1.45)/F_5(\delta = 2.0)$, plotted as full blue and dotted red lines, respectively. The results are plotted on two different scales.

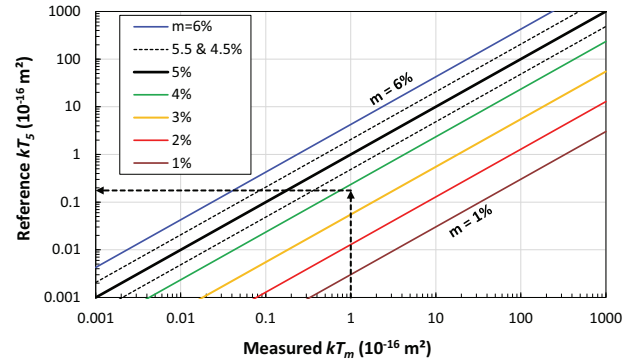


Fig. 8 Nomogram illustrating the calculation of kT_5 as function of the measured kT_m and m

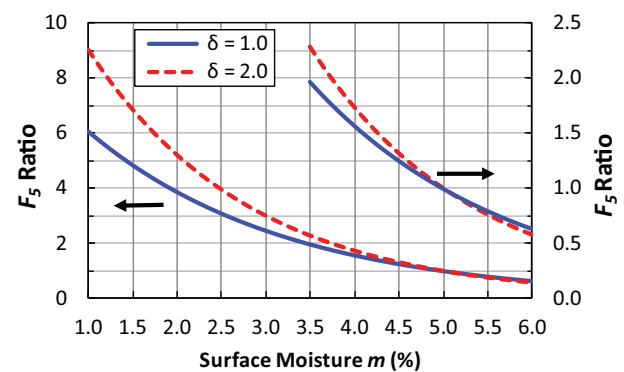


Fig. 9 Sensitivity analysis of the F_5 ratios if exponent δ were 1.0 or 2.0 instead of the adopted 1.45 in Eq. 6

Figure 9 shows that, within the range 3.5–6.0% of m (right hand scale), the F_5 ratios are within 2.3 and 0.6 for $\delta = 2.0$ and $m = 3.5$ or 6.0, respectively. This means that the error of assuming $\delta = 1.45$ when it is in reality 1.0 or 2.0, is acceptable, given that kT values span 5–6 orders of magnitude. For lower m values the error increases significantly (left hand scale).

5 Conclusions

The effect of surface moisture of concrete m , indicated by electrical impedance-based instruments, on the measured value of air-permeability coefficient kT , has been analysed on the basis of 5 independent data sources, comprising 50 different cases, with the following conclusions:

- The suitability of the electrical impedance instrument to monitor changes in the humidity conditions of the surface layers of concrete, previously



established [12, 13], has been confirmed by all data sources

- The change in the coefficient of air permeability kT with changes in surface moisture m can be appropriately expressed by Eq. 2, with high correlation coefficients of the fitted regressions ($\bar{R} = 0.95$). It was obtained by excluding young concrete (< 28 days) for focusing on drying effects after cement hydration.
- In 84% of the 50 cases, the exponent δ of Eq. 2 fell within the range 1.0 – 2.0, with a median value of $\delta = 1.45$. This median value is adopted for the moisture correction process.
- A correction of kT_m values of air-permeability, measured under surface moisture m , is proposed, taking as reference the value of kT for $m = 5.0\%$ (typical moisture content in concrete structures at the ages of several months), called kT_5 . This correction is described by Eqs. 5 and 6. In-situ moisture contents under arbitrary environmental conditions will be discussed in the future study.
- A sensitivity analysis for the cases where δ were 1.0 or 2.0 instead of the adopted value of $\delta = 1.45$, confirms the robustness of the proposed correction.
- For surface moistures m within 4.5% and 5.5% the difference between the measured kT_m values and the corrected kT_5 values is of little practical relevance.
- The corrections are valid for concrete with ages of at least 28 days, when hydration is well advanced, and for surface moistures m within 1.0% – 6.0%. Useful relations were obtained under drying conditions leading to concrete transient moisture states, not in equilibrium and not homogeneous. Scientific validation of the reported relations to steady state conditions should be the object of a future study.
- It is expected that this contribution can be incorporated into future versions of the standards.

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Declarations

Conflict of interest The authors have no conflict of interest to declare.

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