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ORIGINAL ARTICLE

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

Verónica Bueno · Kenichiro Nakarai · May Huu Nguyen · Roberto Juan Torrent · Isao Ujike

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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 ($\overline{R} = 0.95$), 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.

Keywords Concrete · Permeability · Moisture · Drying · Durability

V. Bueno
Materials Advanced Services Sagl, 6877 Coldrerio, Switzerland

K. Nakarai (✉) · M. H. Nguyen
Civil and Environmental Engineering Program, Hiroshima University, 1-4-1 Kagamiyama, Higashi-Hiroshima, Hiroshima 739-8527, Japan
e-mail: nakarai@hiroshima-u.ac.jp

M. H. Nguyen
Department of Bridge and Tunnel, University of Transport Technology, 54 Trieu Khuc, Thanh Xuan, Hanoi 100000, Vietnam

R. J. Torrent
Materials Advanced Services SRL, C1425 ABV Buenos Aires, Argentina

I. Ujike
Department of Engineering, Ehime University, 3 Bunkyo, Matsuyama, Ehime 790-8577, Japan

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

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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 $< 0.001 \times 10^{-16}$ m^2 to $> 100 \times 10^{-16}$ 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 °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 °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 °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 Ø13 × 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 × 300 × 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 $kT_0 = 5.25 \times 10^{-16}$ 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) + *SCM*	EN 197 Class
H0	Holcim Pur-5 N	CEM I 52.5 N
H8M	92% Holcim Pur-5 N + *8% Silica Fume*	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% Fly Ash*	CEM IV/B 32.5 N

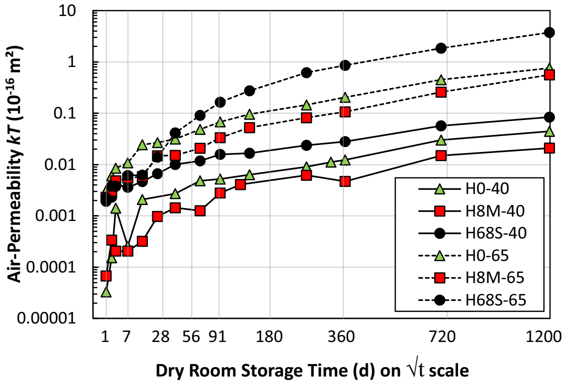

Fig. 1 Changes in *kT* of cubes stored at an age of ≈ 3 months in a dry room (20 °C, 50–65% RH)

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 Cement type*		M1 OPC	M2 OPC	M3 OPC	M4 LFC	M5 OPC	M6 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

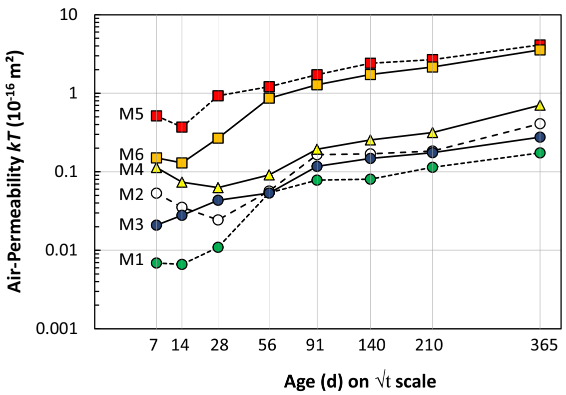

Fig. 2 Changes in *kT* of cubes stored at an age of 48 h in a dry room (20 °C, 35% RH)

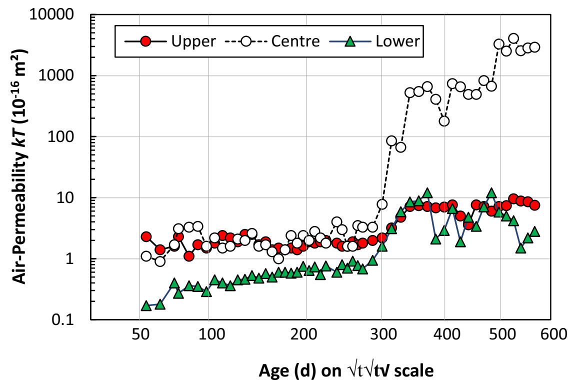

Fig. 3 Changes in *kT* for mix FACUS60 concrete column with embedded steel

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

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

		Laboratory prisms					
Mix code		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

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.

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

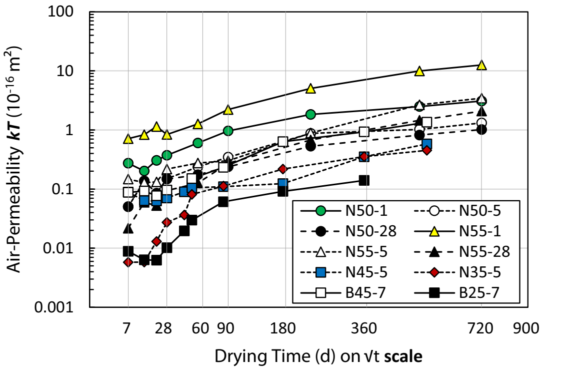

Fig. 4 Changes in *kT* for laboratory prisms (~ 20 °C, ~ 60% RH)

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 °C and 62.1%, respectively.

Simultaneously, three large-scale reinforced concrete mock-up panels (1.5 × 1.5 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 × 1.5 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 × 1.5 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 × 10^{-16} 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 °C (*m* ≈ 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	(–)	kg/m^3	%	% cement	mm	MPa
N	OPC	295	0.550	1845	44	≈ 1%	120	31.9
B	BFSC	303	0.525	1837	43		150	34.4

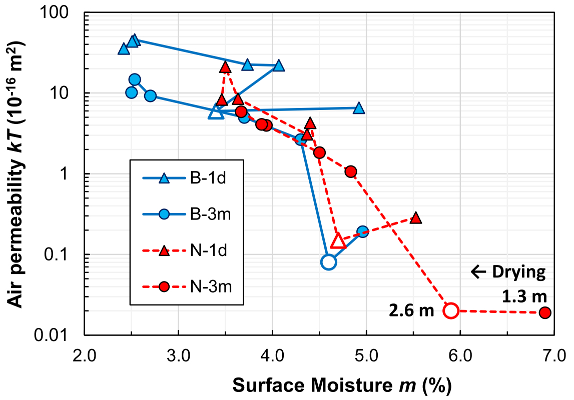

Fig. 5 Relation *kT* vs *m*, showing abnormal data for tests at 2.6 months (larger white symbols)

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:

$$kT = kT_0 \cdot e^{-\delta \cdot m} \quad (2)$$

with *m* expressed in %; only the data with 1.0% ≤ *m* ≤ 6.0% and with $kT \geq 0.001 \times 10^{-16}$ 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 δ = 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, $\delta 28^+$ 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

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

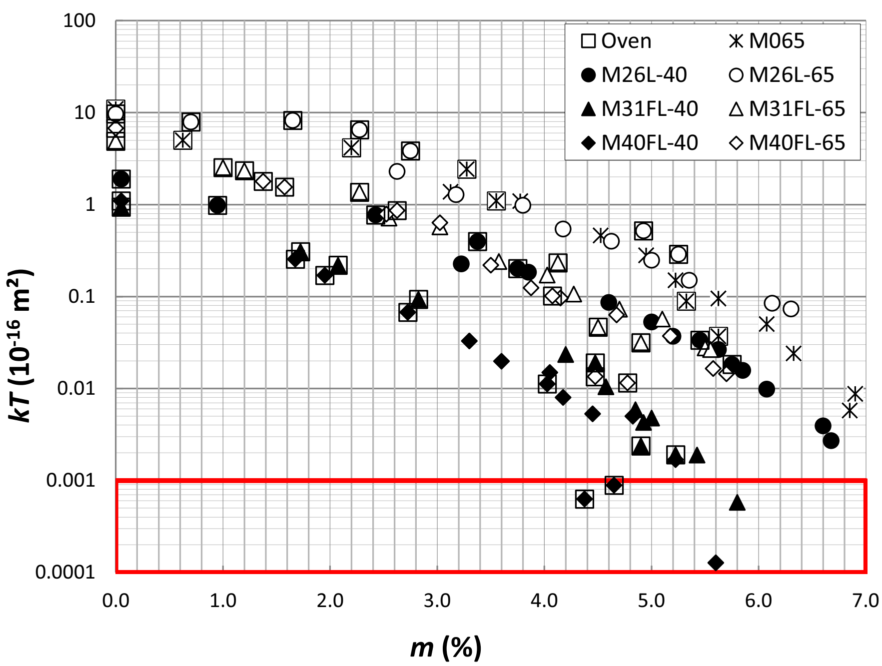

Table 6 Results of fitting Eq. 2 to the data recorded in the researches described in Sects. 3.1, 3.2, 3.3, 3.4, 3.5

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
$\delta 28^{+}$	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		
$\delta 28^{+}$	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	*6 with R < 0.80*	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	
$\delta 28^{+}$	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	
$\delta 28^{+}$	1.78	1.76	1.78	0.66	1.59	1.41	$\delta 28^{+}$	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 δ = 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

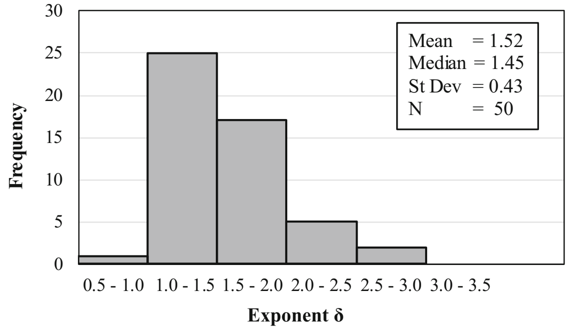

Fig. 7 Histogram of values of exponent δ found in all five reported investigations

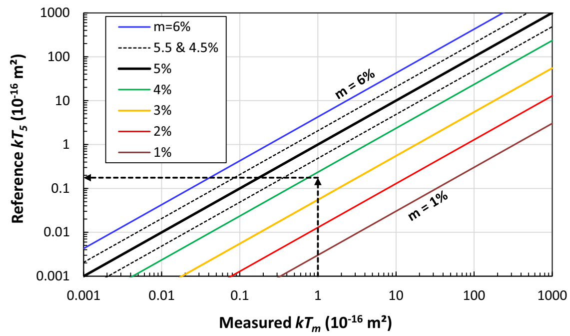

Fig. 8 Nomogram illustrating the calculation of kT_5 as function of the measured kT_m and m

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

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

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 1.0×10^{-16} 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 0.18×10^{-16} 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 δ = 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.

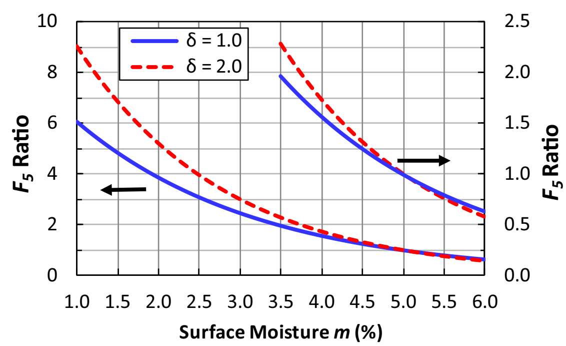

Fig. 9 Sensitivity analysis of the F_5 ratios if exponent δ were 1.0 or 2.0 instead of the adopted 1.45 in Eq. 6

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 δ = 2.0 and m = 3.5 or 6.0, respectively. This means that the error of assuming δ = 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 δ = 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 δ = 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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