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ORIGINAL ARTICLE

Concrete carbonation prediction based on air-permeability tests with moisture compensation

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Abstract Predicting carbonation resistance via early site tests is crucial for controlling the longevity and durability of concrete structures. Therefore, this study aimed to provide a nondestructive approach for predicting carbonation resistance utilizing in situ air-permeability and surface moisture measurements. The Torrent air-permeability method, coupled with surface moisture measurements by the electrical impedance method, was applied to 25 specimens produced using different cement types, water-to-binder ratios, and curing periods to obtain test data at various ages from 1 to 18 months; the carbonation depths were measured at 6, 12 and 18 months. To overcome the challenge of the moisture effect on measured values during the drying process, the kT_5 indicator, permeability coefficient at the reference moisture of 5.0% was utilized. Strong correlations between kT_5 and the carbonation rates were obtained that allowed the latter's prediction from tests of air-permeability and surface moisture performed at relatively early ages (e.g., 1 or 3 months). Guidance on the procedure is outlined.

Keywords Cover concrete · Carbonation resistance · Non-destructive test · Permeability · Durability

1 Introduction

Concrete cover is the least distance between the surface of the embedded reinforcement and the exposed surface. It plays a crucial function as the first shielding, protecting the inner part of a concrete structure and the embedded steel reinforcement [1–3]. Nonetheless, it is the most permeable part of the structure because of its higher porosity than that of the concrete's internal part. The movement of gases, liquids, and ions through this layer occurs during the service life of concrete structures and can cause the deterioration of reinforced concrete structures [4–6]. Thus, an appropriate assessment of the transport properties of the concrete cover is crucial for controlling the longevity and durability of concrete structures [7–9].

Depending on the process' driving force and the transported matter type, transport qualities can be characterized as diffusion, absorption, or permeation [2, 8]. Among these, air-permeability, a reliable characteristic representing permeation, is closely

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related to the pore structure of concrete [2, 8, 10] and can be measured via destructive and non-destructive test methods [11–13]. Pertaining to the non-destructive aspect, several permeability assessment methods have been proposed and validated [14–18]. Among these methods, a double vacuum cell test, Torrent's air-permeability test, was proposed to determine the coefficient of permeability *kT* and the affected depth [15]. The application of the method was preliminarily verified via comparison with the Cembureau method [19, 20].

Indeed, the Torrent air-permeability test has been extensively applied as a non-destructive method for quality control of concrete on site without damaging its structures [15, 21]. Numerous studies have employed the *kT* measured by the Torrent method, as a robust durability indicator to discuss and verify other indices or other concrete durability characteristics [21–23]. Moreover, it has been considered a durability design factor for the residual service life of reinforced structures affected by carbonation and chloride ingress [5, 24].

On the other hand, the measured air-permeability values strongly depend on the drying condition (i.e., the surface moisture content, *m*) of the measured concrete, as observed via the increment in *kT* of around three orders of magnitude from near saturation to oven-drying at 105 °C [7, 25–27]. For instance, Parrott investigated the correlation between moisture conditioning and transport properties at the surface of concrete test specimen [7]. Based on the experimental results, he found that air-permeability was sensitive to changes in the moisture content of the concrete, especially at relative humidity $(RH) > 60\%$. The corresponding sample preconditions were recommended as a countermeasure to prevent the effect of the surface moisture content. Jacobs studied changes in the gas permeability of partially saturated concrete [26] and demonstrated a linear correlation between the gas permeability and water content in concrete pores using a logarithmic function. Romer monitored the influence of surface moisture content on *kT* values in controlled environmental conditions for a period of up to one year [27]. They found that the absolute values of *kT* depend on the concrete age and its surface moisture conditions. The reduction in the *kT* value owing to the elevated water saturation of concrete can underestimate the intrinsic permeability. As a result, changes in the degree of saturation of the pore system were reflected in variations in surface moisture content and variable blockage of gas flow through the pore system. In addition, it was found that moisture remaining in the pores or low-permeability concrete can evaporate into the test cell at very low vacuum pressures, artificially raising its pressure [28].

To address the above problems, several studies have focused on attempts to compensate for the effect of moisture on *kT*, or on methods used to assess *kT* at moisture equilibrium [29–33]. In early attempts to compensate for the effect of moisture on *kT*, two different techniques were investigated: James H_2O meter (that failed) and the Wenner method [29]. A solution was proposed to compensate for the influence of moisture using a combination of *kT* and electrical resistivity measurements (by the Wenner method), which failed owing to difficulties in measuring the electrical resistivity on-site [34] and to the strong effect of the binder type on that property. Another solution requested a waiting time, such as 3–4 weeks after the completion of curing or 2–5 days after the last exposure to moisture, to withstand the high moisture influence (e.g., rain, sea spray) [35, 36]. Furthermore, incorporating in-situ and laboratory-based permeability testing techniques was suggested as part of an integrated strategy [37]. This strategy aimed to reduce the influence of moisture on in situ permeability measurements. The test results indicated that the controlled moisture content did not significantly affect the *kT* value in the context of the overall classification. However, no specific equation was provided to complement the effect of moisture content on the *kT* value. Based on experimental data, Misak et al. [30] proposed an equation to assess the impact of moisture content *h* (measured by KAKASO capacitive humidity meter) on the *kT* values:

$$kT = kT_0 \times e^{-\alpha . h} \tag{1}$$

where kT_0 and α are compensation factors for the *kT* value measured at moisture *h*. Based on 153 test results, the proposed values of kT_0 and α were 5.25×10^{-16} m^2 and 0.862, respectively. In Switzerland, a study conducted at the Empa laboratory proved the suitability of a device to assess the surface moisture *m* of concrete based on changes in electrical impedance [27]. Recently, a comprehensive study was conducted on the relationship between *m* and *kT* for drying concretes [38]. Based on a large database from five different independent sources and a robust analysis process, a novel practical approach was proposed to compensate for the effect of moisture content m on *kT*. The proposed approach uses the kT_5 value, which corresponds to a moisture content of 5.0%, as a reference index. The obtained results indicate a promising application of Torrent air-permeability for the flexible assessment of air-permeability at various surface moisture conditions.

In fact, assessing concrete carbonation resistance through Torrent air-permeability has been attended to due to their close correlations and the advantages of the Torrent test as an in-situ non-destructive method [23, 39, 40]. However, thus far, assessing concrete carbonation resistance through Torrent air-permeability considering the effect of surface moisture content has not been investigated, although a potential approach utilizing the application of the kT_5 concept was proposed, as mentioned above.

Taking into account the literature results summarized above, the objective of the present study is to establish a unified approach for *kT* measurement at any moisture state to assess and predict the concrete carbonation resistance based on extensive experimental data in a laboratory. To realize this, the Torrent air-permeability was applied to various specimen qualities to collect the *kT* values at the ages of 1, 3, 6, 12, and 18 months (hereafter called kT_m at the surface moisture content m). The correlations between kT_5 calculated from these kT_m values and the corresponding carbonation rates collected on the specimens were established and discussed to validate the usability of kT_5 as an excellent index for predicting carbonation resistance.

2 Experimental program

2.1 Test variables

To analyze the changes of air-permeability and carbonation rate for different concrete qualities, 25 concrete specimens were prepared with three types of cement, nine water-to-binder ratios (W/B), and five curing conditions, as indicated in Table 1. Here, 20 of the 25 specimens were collected from four earlier works [23, 31, 40, 41]. Details on the specimens, such as the materials, mix compositions and curing procedures, can be found in the earlier publications. To widen the scope of this investigation to include other concrete qualities, five more specimens were cast using the same materials as for the prior specimens: OPC concretes with greater W/B (65% and 75%) and HPC concrete with a W/B of 41%. After curing, the air-permeability kT_m and the surface moisture *m* were measured at five different ages and the carbonation depth at 6, 12, and 18 m, as described below.

2.2 Materials and mix proportions

Three types of cement were used in the concrete mixes: ordinary Portland cement (OPC), blast-furnace slag-type B cement (BBC), and high early strength Portland cement (HPC) according to JIS R 5210 [42] and JIS R 5211 [43]. Fine (S) and coarse (G) aggregates of crushed porphyry were used. Expansive agents of the ettringite type were used. To meet the required workability and improve the performance of fresh concrete even under cold weather conditions, chemical agents were utilized, including superplasticizers (SF500U and type-I VP700) and AE water-reducing agents (EX60 and SV10L) (AD). To mix the cement components, tap water was used. The 13 mix compositions and fresh concrete properties are listed in Table 1.

2.3 Specimen preparation

Thirteen concrete mixes were investigated to monitor *m*, kT_m, and carbonation depth. A manufacturer produced ready-mixed concretes for mixes HPC41 and BBC53E. The remaining concrete mixtures were prepared in the laboratory with the use of a pan-type mixer. Prior to casting, the slump (or slump flow), and air content of fresh concrete were measured. The prismatic specimens were then cast, as shown in Fig. 1. The dimensions of the six large prismatic specimens (mixes HPC41 and BBC53E) were 600 × 900 × 600 mm (see Fig. 1a). Those of the two small prismatic specimens (mixes OPC65 and OPC75) were 400 × 100 × 100 mm (see Fig. 1c), and those of the 17 medium prismatic specimens (for the remaining mixes) were 800 × 300 × 200 mm (see Fig. 1b).

The specimens were kept in the moulds for the periods indicated in Table 1 (i.e., 1, 3, 5, 7, and 28 days) to create 25 different concrete qualities, protecting the exposed surface from evaporation and

Table 1 Mix compositions, fresh concrete properties, and curing of concrete specimens [23, 31, 40, 41]

Concrete mix	W/B	Slump (mm)	Slump flow (mm)	Air (%)	s/a[a] (vol%)	Mix composition (kg/m^3)						In-the moulds curing period (d)	Specimen size	References
						W	C	Ex	S	G	AD			
OPC25	0.25	–	600	2.0	39.2	170	680	0	580	894	13.06[b]	5	Medium	[23]
BBC25	0.25	–	600	2.0	39.2	170	680	0	580	894	13.06[b]	7	Medium	[31]
OPC35	0.35	–	600	2.0	41.0	170	486	0	676	973	9.71[b]	5	Medium	[23]
HPC41	0.41	120	–	4.5	45.2	171	417	0	753	935	2.84[c]	1,3,28	Large	This study
OPC45	0.45	80	–	4.5	50.4	170	378	0	758	1013	2.84[c]	5	Medium	[40]
BBC45	0.45	80	–	4.5	50.4	170	378	0	758	1013	2.84[c]	7	Medium	[31]
OPC50	0.50	80	–	4.5	50.4	170	340	0	789	1012	2.55[c]	1,5,28	Medium	[40]
BBC50	0.50	80	–	4.5	50.4	170	340	0	789	1012	2.55[c]	1,7,28	Medium	[31]
BBC53E	0.53	120	–	4.5	46.3	175	310	20	796	933	2.64[d]	1,7,28	Large	[31]
OPC55	0.55	80	–	4.5	50.4	170	309	0	814	1003	2.23[e]	1,5,28	Medium	[41]
BBC55	0.55	80	–	4.5	50.4	170	309	0	814	1003	2.23[e]	1,7,28	Medium	[31]
OPC65	0.65	80	–	4.5	48.9	170	262	0	984	933	2.15[e]	1	Small	This study
OPC75	0.75	80	–	4.5	48.9	195	262	0	864	906	2.05[e]	1	Small	This study

[a] s, a denote the volume of fine aggregates and total volume of aggregates, respectively

[b,c] Superplasticizers: SF500U and VP700-type I, JIS A 6204:2011[49]

[d] AE water-reducing agent, EX60, JIS A 6204:2011[49]

[e] AE water-reducing agent, SV10L, JIS A 6204:2011 [49])

stored in a room at ~ 20.7 °C. Then, specimens were demoulded and exposed to air as follows. The six large prismatic specimens (Fig. 1a) and the two small prismatic specimens (Fig. 1c) were exposed without sealing, whereas the 17 medium prismatic specimens were sealed using aluminium foil with two 800 × 300 mm surfaces left exposed (Fig. 1b). The two small prismatic specimens were stored in a controlled room at 20 °C /60% RH, whilst the other specimens were stored in a normal room at 21.2 °C / 62.1% RH on average. Carbon dioxide concentration was around 0.04%, as recorded by the ZG106 CO_2 monitor. Four test locations were selected on each measurement surface, avoiding large bubbles and visible cracks to limit their effects on the results.

2.4 Test methods

At each measurement age, the tests (surface moisture content, air permeability, and carbonation) were directly conducted on the given surfaces, i.e., vertical surfaces of the large, medium, and small specimens with the dimensions of 900 × 600 mm, 800 × 300 mm, and 400 × 100 mm, respectively.

2.4.1 *Surface moisture measurement*

The moisture content of the specimens *m* was monitored throughout the experiment. An impedance-based CMEXpert II Concrete Encounter Moisture Meter (Tramex, Ireland) was employed in compliance with the American Society for Testing and Materials (ASTM) standard F2659 [44]. The device works by sending a low-frequency signal through parallel co-planar electrodes into the concrete. Its suitability for monitoring changes in the surface moisture content of concrete specimens has been verified in previous investigations, despite the fact that it offers indirect readings [32, 38, 45]. The specimens were measured at the ages of 1, 3, 6, 12, and 18 months later. The arithmetic means of the surface moisture content values measured on four test locations are reported.

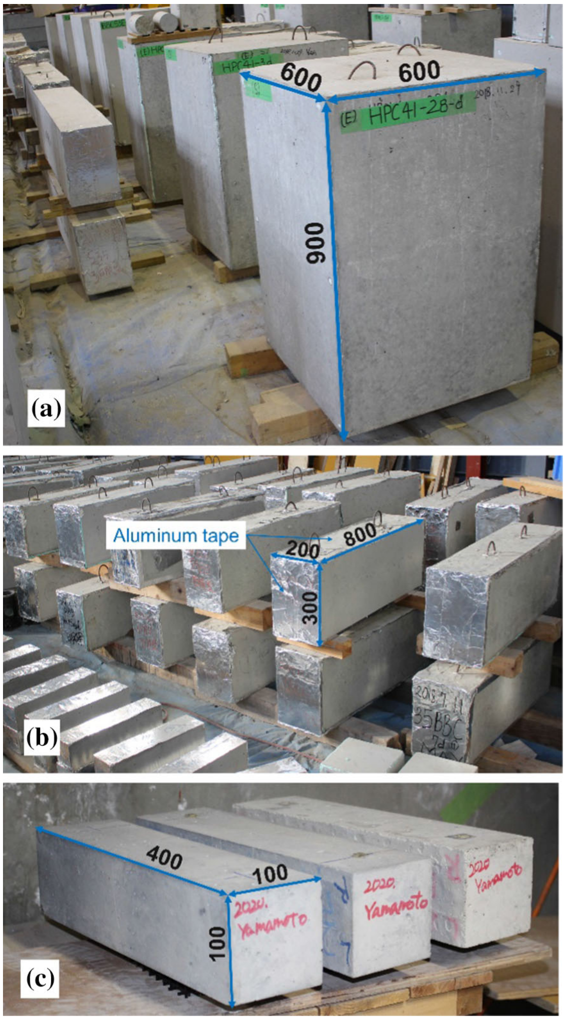

Fig. 1 Overview of prismatic specimens (mm): **a** 600 × 900 × 600 specimens, **b** 800 × 300 × 200 specimens, and **c** 400 × 100 × 100 specimens

2.4.2 *Air-permeability measurements*

The kT_m was assessed by utilizing a Torrent tester, PermeaTORR AC (Active cell) in accordance with the Swiss standard SN 505 262/1:2013 [15, 20]. The tester uses a double chamber cell to create a unidirectional airflow toward the central chamber so that kT_m can be calculated using a suitable model [15, 46]. After the surface moisture measurement, the Torrent tests were conducted at 1, 3, 6, 12, and 18 months. The geometric mean of the values obtained at four test locations was utilized to compute the kT_m values.

2.4.3 *Carbonation depth measurements*

After the surface moisture and air permeability measurements, five cores (30 mm, length 50 mm) were drilled at 12 and 18 months for the large and medium specimens and split. The small prismatic specimens were split at 6 and 12 months. Detailed measured carbonation depths of the specimens are provided in Appendix 1. The carbonation depth was measured by spraying the split surface with 1% phenolphthalein indicator solution. The averages of five and ten measured points of the split surfaces were calculated to evaluate the concrete carbonation progress (the carbonation rate was computed as the carbonation depth divided by the square root of the exposure time, averaging the values obtained at both ages).

3 Results and discussion

3.1 Assessing concrete carbonation resistance via kT_m index

Correlations between the carbonation rate and kT_m—the latter measured at the ages of 1, 3, 6, 12, and 18 months- are presented in Fig. 2 (dashed lines). Regardless of the cement type, for each measurement age, the plots indicate a single correlation between

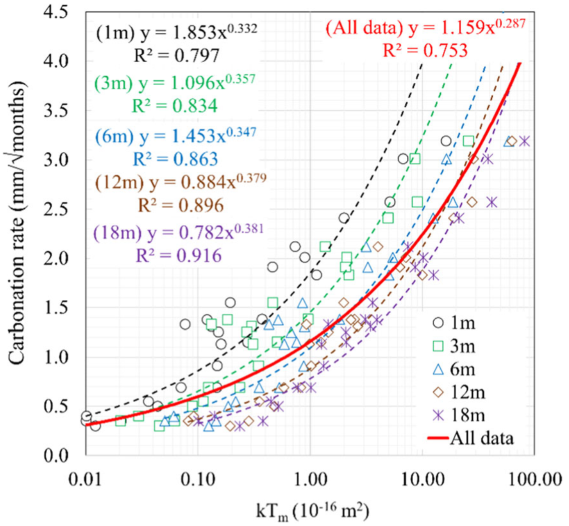

Fig. 2 Correlation between kT_m and carbonation rate at the ages of 1, 3, 6, 12, and 18 months

carbonation rate and kT_m, for the 25 concrete specimens, which agrees with and expands the findings of previous studies [22, 47, 48]. The resulting high coefficients of determination ($R^2 \geq 0.797$) validated the regressions obtained by fitting power lines. However, the results indicated that the correlation is dependent on the age at which kT_m was measured and the resulting moisture conditions. As shown in Fig. 2, the coefficient of determination gradually increases with the age of the kT_m (from 0.797 to 0.916). A single estimated red line covering all data with high correlation could not be obtained ($R^2 = 0.753$). It means that kT_m can be proposed as a promising durability index for predicting the carbonation progress of different concrete types, when the measurement age could be selected, in particular, when later measurement age was selected.

Figure 3 shows the significant changes in kT_m with surface moisture m for the 25 concrete specimens investigated. A monotonic increase in kT_m for lower m (drier concrete) can be observed for each mix. In other words, the moisture conditions of the specimens (i.e., the surface moisture content of the specimens) play a vital role in obtaining representative measurements of the air-permeability coefficient. Even though the short-age correlations in Fig. 2 are acceptable [20, 40], later age measurements of kT_m yield better coefficients of determination. In particular, the kT_m values at 18 months are considered highly representative measurements for predicting the carbonation progress.

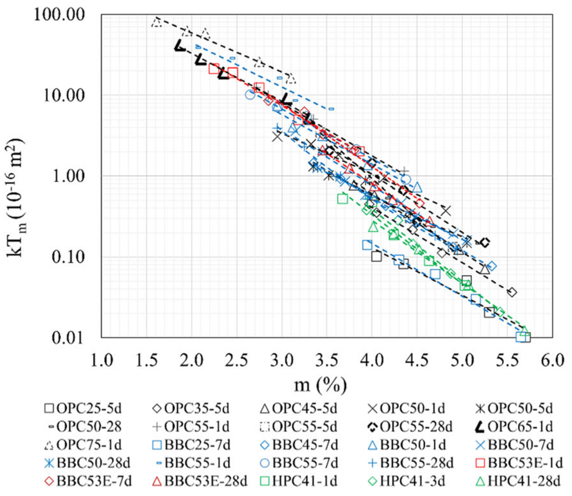

Fig. 3 Correlation between kT_m and m

Nevertheless, a sufficient drying stage strongly depends on the surrounding conditions during the exposure period for in situ measurements. Even under laboratory conditions, a late-age measurement (e.g., at 18 months) requires a prolonged waiting time for representative measurements, which is not practical. Thus, concrete structures' changing surface moisture content is the main barrier preventing the above approach for assessing concrete carbonation resistance through kT_m. To address this issue and provide a flexible approach for predicting the concrete carbonation resistance, a new approach utilizing kT_5 was presented in the next section.

3.2 Predicting concrete carbonation resistance based on the kT_5 index

This section proposes a flexible and practical approach for predicting the concrete carbonation resistance using the kT_5 index. Herein, kT_5 is the air-permeability value corresponding to a moisture $m = 5.0\%$ [38], computed as,

$$kT_5 = F_5 \times kT_m \tag{2}$$

where F_5 is a compensation factor for the value of kT_m measured at moisture m, and is computed as follows,

$$F_5 = e^{1.45(m-5.0)} \quad \text{valid for } 1.0\% \leq m \leq 6.0\% \tag{3}$$

Equations (2) and (3) were derived from the analysis of the variation of kT with m during the drying of 50 concrete mixes which originated from five different sources [38]. Ideally, for a particular concrete and m ranging between 1 to 6%, the kT_5 value is expected to compensate the effect of m on kT_m and remain unchanged [38]. To clarify this idea, in this study, the kT_5 values at 1, 3, 6, 12, and 18 months were calculated based on Eqs. (2) and (3), and correlations with the carbonation rate were established. Figure 4 shows the correlations between the carbonation rate and kT_5 calculated from kT_m and m at the ages of 1, 3, 6, 12, and 18 months. Two aspects are worth mentioning in Fig. 4. First, for each measurement age, especially for early measurement ages from 1 to 6 months, the scatter of the kT_5 values is smaller compared with that of the kT_m values shown in Fig. 3. This supports the use of the former as a valid indicator of the air-permeability of the mix. Second, regardless of the measurement age, a single line (solid red line)

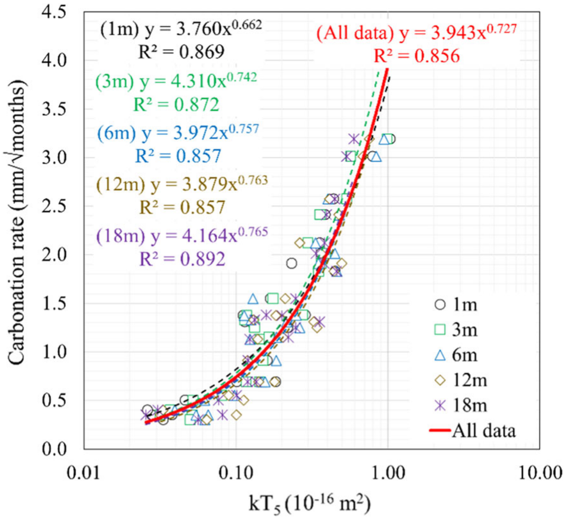

Fig. 4 Correlation between carbonation rate and kT_5 calculated from kT_m and m

giving unique correlations with high coefficients of determination ($R^2 = 0.856$) can be established between the carbonation rate and kT_5 for all concretes. This means that the results in Fig. 4 indicate the differences between the regression dashed lines (carbonation rate and kT_5) obtained for each testing age, and the overall red solid line, are insignificant. Additionally, the values for three binders follow reasonably well the general trend and, therefore, are not differentiated.

To find out the most appropriate measurement procedure for accessing carbonation resistance utilizing the kT_5 index, correlations between carbonation rate and kT_5 calculated from different accumulated ages were established and discussed. In detail, correlations between carbonation rate and kT_5 calculated from double and triple measurements were then established, as presented in Figs. 5a and b, respectively. The procedure to calculate kT_5 from single, double, triple, and accumulated measurement ages was presented in Appendix 2. The result indicates that the strongest correlation was found in the case of kT_5 calculated at all accumulated ages rather than other measurement cases. The obtained R^2 value of 0.914 for all accumulated ages (1 + 3 + 6 + 12 + 18 months) was higher than those from single (Fig. 4), double (Fig. 5a), and triple (Fig. 5b) measurements. Outcomes suggested that the adopted approach was the most appropriate for accessing carbonation resistance under a standard environmental condition (∼ 20 °C and ∼ 60%RH). Based on the found correlation, concrete carbonation resistance can be assessed by utilizing the kT_5 index, as shown in Eq. (4).

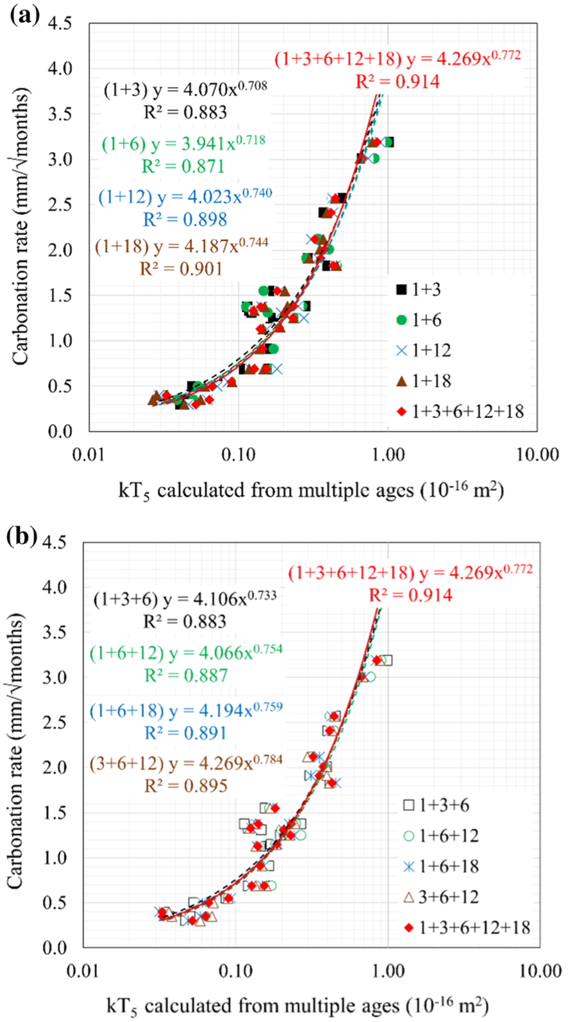

Fig. 5 Correlations between carbonation rate and kT_5 calculated from: **a** double and **b** triple measurements and all measurements at the five ages

$$K_c = 4.27kT_5^{0.77} \tag{4}$$

where K_c denotes carbonation rate, (mm/$\sqrt{month}$), obtained from concrete specimens with OPC, BBC, or HPC around 20 °C /60%RH /0.04%CO_2, kT_5 is the air-permeability value, (10^{-16} m^2), corresponding to a moisture $m = 5.0\%$, and is calculated from kT_m and m via Eqs. (2) and (3).

For a detailed comparison of kT_m and kT_5 for predicting concrete carbonation resistance, their

Table 2 Ratio of predicted to measured carbonation rates for different kT indicators

Ratio between predicted (using kT_m or kT_5 values) and measured carbonation rate											
Index	kT_m[a]	kT_5 predicted from single or multiple kT_m at different age(s) (months)									
		1	3	6	12	18	1 + 3	1 + 6	3 + 6	1 + 3 + 6	1 + 3 + 6 + 12 + 18
Mean	1.076	0.959	0.965	1.088	1.134	1.048	1.026	1.031	1.021	0.997	1.028
SDs	0.427	0.260	0.231	0.291	0.356	0.283	0.240	0.252	0.247	0.234	0.230
CoV (%)	39.7	27.1	24.0	26.7	31.4	27.0	23.3	24.4	24.2	23.5	22.3

[a] kT_m denotes values calculated from the 1st to 18th months, i.e., all data reported in Fig. 2

accuracies were further evaluated using additional analytical indices: mean, standard deviation (SDs), and coefficient of variation (CoV) of the ratio of the predicted carbonation rate to the measured carbonation rate (see Table. 2). Here, the carbonation rates were predicted by using kT_m in the equation for all the data ($K_c = 1.16kT_m^{0.29}$) in Fig. 2 or kT_5 in Eq. (4). As expected, the mean, SDs, and CoV indices were improved significantly from 1.076, 0.427, and 39.7% for kT_m to 1.028, 0.230, and 22.3% for kT_5, respectively. The results verified the higher accuracy of the kT_5 index for predicting concrete carbonation resistance. Furthermore, the results indicated that variations in the analytical indices using kT_5 predicted from multiple measurement times (geomean) were slightly reduced compared to those from a single measurement. These imply that the measured coefficient of air-permeability, kT_m, can be used to obtain the moisture-compensated air-permeability indicator, kT_5, for accurately predicting the carbonation resistance of concrete. They also indicate that multiple measurements can further improve accuracy.

On the basis of the obtained results, a novel approach for predicting concrete carbonation resistance using kT_5 as an indicator can be formulated as described below.

The proposed procedure used to predict the carbonation rate consists of the following steps:

1. Define concrete lots following, for instance, the recommendations of [20].
2. Measure the kT_m values and the surface moisture m on at least six random test locations of each lot, at an age that ranged from 1 and 18 months, preferably between 1 and 6 months. Multiple measurements can be conducted at two or more different ages for improved prediction.
3. For each single age measurement, kT_5 value is calculated from the geometric mean of kT_m and average moisture m, calculated from single measurement age, applying Eqs. (2) and (3). For multiple measurements, kT_5 value is calculated from the geometric mean value of kT_5 at several measurement ages, as presented in Appendix 2.
4. Calculate the predicted carbonation rate K_c by applying Eq. (4).

4 Conclusions

This study presented and validated the application of the Torrent method to measure the coefficient of air-permeability kT_m, coupled with the parallel measurement of the surface moisture m for the assessment of the concrete carbonation resistance. Both non-destructive tests were applied on 25 concretes of various qualities, which were produced by using different cement types, W/B ratios, and curing periods to collect kT_m and m values measured at the ages of 1, 3, 6, 12, and 18 months. At ages of 12 ± 6 months, the carbonation depth was measured, from which the carbonation rate of each mix could be computed based on the assumption of a "square-root law" of the carbonation process. The measured values of kT_m increased whilst those of m decreased with age owing to the continuous exposure to a relatively dry environment. For each mix and age of test, a kT_5 value –corresponding to a reference moisture content of 5.0%– was computed, which compensated for the effect of m on kT_m. Strong correlations were found between the calculated kT_5 and the corresponding carbonation rates. These correlations indicated the usability of kT_5 as a good indicator for predicting the carbonation resistance of various concrete qualities, for which a simple procedure was proposed.

This study's findings contributed to the establishment of a simple and practical method for predicting carbonation resistance from the moisture-compensated index, kT_5. In practice, the proposed Eq. (4) can be employed flexibly as a promising solution for predicting carbonation resistance of concrete structures produced by OPC, BBC, or HPC under a drying process at a standard condition (i.e., around at temperature/RH of 20 °C /60%). Given the limitation of this study, the approach is valid with three cement types at the standard condition. Thus, further investigations should be conducted with other binders, such as fly ash or limestone filler cement, to clarify the extended application of the proposed approach in the broader range. In addition, the effect of moisture state on carbonation progress under various environmental conditions will be another research topic in the future.

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Declarations

Conflict of interest Author declares that they have no conflict of interest.

Appendix 1

Table 3 shows the carbonation depth and carbonation rate of the concrete specimens used in this study.

Table 3 Carbonation depth and carbonation rate of the concrete specimens used in this study

Specimen name	Carbonation depth (mm)			Carbonation rate (mm/$\sqrt{\text{month}}$)
	6 m	12 m	18 m	
OPC25-5d	–	1.23	1.45	0.35
OPC35-5d	–	1.92	2.30	0.55
OPC45-5d	–	2.31	2.99	0.69
OPC50-1d	–	4.57	5.96	1.38
OPC50-5d	–	3.07	3.88	0.91
OPC50-28	–	2.32	2.97	0.69
OPC55-1d	–	5.99	7.94	1.83
OPC55-5d	–	4.54	5.58	1.31
OPC55-28d	–	4.51	5.23	1.25
OPC65-1d	6.21	8.95	–	2.57
OPC75-1d	7.51	11.15	–	3.19
BBC25-7d	–	1.49	1.62	0.40
BBC45-7d	–	4.51	5.67	1.33
BBC50-1d	–	7.54	8.89	2.12
BBC50-7d	–	5.05	6.78	1.55
BBC50-28d	–	3.61	4.91	1.13
BBC55-1d	–	10.21	12.90	3.01
BBC55-7d	–	6.69	8.69	2.01
BBC55-28d	–	4.92	5.78	1.38
BBC53E-1d	–	8.24	10.35	2.41
BBC53E-7d	–	6.62	8.07	1.91
BBC53E-28d	–	3.92	4.89	1.15
HPC41-1d	–	1.72	2.15	0.50
HPC41-3d	–	1.19	1.50	0.35
HPC41-28d	–	1.05	1.25	0.30

Appendix 2

The procedure to calculate kT_5 from single and multiple (double, triple, and accumulated) measurement ages can be assessed by the following equation:

$$kT_5 = \sqrt[n]{kT_{5,1} \times kT_{5,3} \times \ldots \times kT_{5,i}} \quad \text{(B1)}$$

where $kT_{5,i}$ is a value calculated at i-th measurement, utilizing Eqs. (2) and (3); kT_5 is the geometric mean value of $kT_{5,i}$ values; n is the total number of measurements (1 for kT_5 at single age, 2 for kT_5 at double ages, 3 for kT_5 at triple ages, and 5 for kT_5 at accumulated ages).

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