INFLUENCE OF CARBONATION ON TORRENT AIR PERMEABILITY OF CONCRETE

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Abstract. Air permeability testing is increasingly being used to measure the impermeability of concrete and to estimate the durability of reinforced concrete structures using this property. This paper presents the results of a preliminary study on the influence of the carbonation of concrete on its air permeability measured using the Torrent apparatus. Three batches of concrete made with CEM I cement and differing in the w/c ratio (0.45, 0.50, and 0.55) were tested. The influence of the relative humidity of concrete on the air permeability index kT was assessed using relationships available in the literature. It was shown that in carbonated concrete, these relationships need to be modified. The air permeability values obtained in tests are lower than the theoretical values calculated using the equation. The results obtained suggest that the effect of carbonation on the air permeability of concrete is significant and further research in this area is highly recommended.

Keywords: Concrete, carbonation, air permeability, durability, torrent.

1. Introduction

Air permeability is increasingly being used to assess the potential durability of reinforced concrete structures. Such tests are usually carried out on newly constructed structures to confirm that the reinforced concrete structure has been constructed with concrete of a sufficient quality to guarantee the required service life [1, 2]. Provisions on the required air permeability of concrete depending on the exposure class are also included in the Swiss standard SIA 262/1 [3]. Of the seven types of concrete defined there, indicative values for the kT factor are given for five (see Table 1). The requirements apply to concrete in exposure class XC4 and vary according to exposure class XD, which means that the key environmental factors here are carbonation and contact with chloride ions not originating from seawater. In the case of three types of concrete (namely C, D, and E) the requirements are more lenient.

Less commonly, air permeability is used to diagnose existing structures that have been in service for some time [4]. Such a diagnosis should take into account the effect of carbonation on the result of the air permeability measurement of the concrete.

Most reinforced concrete structures are exposed to carbon dioxide and become carbonated. This process causes a sealing of the concrete structure which, over time, should lead to a reduction in its permeability. This can lead to an erroneous, better-than-actual, assessment of the quality of the concrete and its expected service life.

The effect of carbonation is ignored in permeability tests on both laboratory-prepared specimens and newly-constructed structures, which seems reasonable. Laboratory specimens are usually no more than 28–90 days old, which means that the concrete carbonation reaction has affected such a thin layer of material that it does not significantly affect the air permeability test results. The situation is similar for newly constructed structures, as the permeability test is carried out at a similar time after the concrete has been cast [5].

This does not mean that there is no research into the relationship between the permeability of concrete and its carbonation. However, they are mainly aimed at correlating these two durability parameters so that the carbonation factor K_c can be estimated from the result of the air permeability test [6–8]. Based on such a relationship proposed by Neves et al. [8], calculations have also been carried out using the Monte Carlo simulation method to obtain distributions of a random variable describing the service life of the structure [9].

The relative humidity of concrete has a very large and well-documented influence on the results of an air permeability test [10–14]. However, there are no clear correlations for converting the result at different moisture levels. This is complicated by the fact that the moisture content of concrete can be expressed in different ways (e.g., saturation level, mass water content of concrete, and relative humidity of air in concrete pores) and measured by different methods, between which there are no established relationships for converting the results. Another complication is that the distribution of moisture at a depth in concrete can vary depending on whether the concrete has been ex-

Description	Concrete type						
	A	B	C	D	E	F	G
Exposure Classes	XC1 XC2	XC3	XC4 XF1	XC4 XD1 XF2	XC4 XD1 XF4	XC4 XD3 XF2	XC4 XD3 XF4
Air permeability kT$_s$ (10^{-16} m^2)	—	—	2.0	2.0	2.0	0.5	0.5

TABLE 1. Indicative values of the air-permeability test results (acc. to SIA 262/1 [3]).

posed to precipitation or dried out prior to testing. This is, therefore, the scope for further research.

Nevertheless, attempts have been and continue to be made to establish a relationship between the Torrent permeability coefficient kT and concrete moisture content. Such a relationship has been proposed by Torrent [15, 16] and is based on concrete moisture content testing by low frequency AC impedance measurement using the CMEXpert II Concrete Encounter Moisture Meter. The result of this measurement is identified with the value of the mass water content of the concrete expressed as a percentage. Another relationship, based on the moisture content measurement using the KAKASO capacitive moisture meter, was presented by Kucharczyková et al [17]. The moisture content of the concrete was also expressed in terms of mass water content, but its values were calculated from a calibration curve based on the readings of the KAKASO moisture meter.

What the two relationships above have in common is their exponential nature. However, the differences lie in the values of the parameters of the exponential function and the assumption of a different value of the reference moisture content as a basis for calculating kT at a different concrete saturation. It should also be added that the simple nature of the given relationships, which do not even take into account the basic characteristics of the concrete, such as the type of cement used or the w/c ratio, indicates that it is only possible to make a rough estimate of the air permeability at a moisture content different from that at which the measurement was made.

Similarly, they do not take into account the relationship between the depth of carbonation of the concrete and the change in its permeability relative to its original value. Clearly, such a relationship must also take into account the effect of concrete moisture. An attempt to relate these three parameters was made by Bonnet and Balayssac [18], with additional consideration of the Wenner resistivity of the concrete and the pore solution. However, the results of the research and analysis presented in Bonnet's work do not allow the influence of carbonation on the variation of the value of the kT coefficient to be identified, as the authors had a different objective, which was to allow the degree of concrete saturation and the depth

of its carbonation to be determined on the basis of the measurement of the resistivity by the Wenner method and the air permeability of the concrete. The question of the influence of carbonation on the value of the kT coefficient in the long term remains open.

The answer to this question is made more difficult by the conditions of the concrete carbonation test, when this test is carried out by subjecting the concrete to accelerated carbonation. This is usually done in a climatic chamber at a constant RH = 60 %. This causes drying of the concrete specimens, which are usually cured in water for 28 days, and stored in laboratory conditions prior to testing. This affects the moisture distribution in the material, which has a direct effect on the permeability test results. In addition, one of the products of the carbonation reaction is water. On a macro scale and in the natural carbonation process, this water is not significant, but in an accelerated process, it is another factor that can significantly affect the permeability results. This is particularly true as the carbonation reaction in concrete takes place at different intensities, both in depth and in time.

It is clear from the above short literature review that studying the effect of carbonation on the air permeability of concrete is not a trivial matter. For this reason, the authors of the study decided to begin by attempting a qualitative rather than quantitative assessment of this influence. One of the reasons for this is that there are very few relationships between the kT coefficient and the moisture content of concrete and they are very generalised. In this study, the relationship proposed by R. Torrent [15, 16] was used. However, it has only been used to "dissect" the effect of carbonation on the permeability from the results obtained. This is based on the assumption that the effect of concrete carbonation manifests itself in the form of a difference between the result obtained from tests at a given moisture content and the theoretical result calculated from the relationship adopted. In view of the factors mentioned above, which complicate the study and the interpretation of its results, the research presented in this article should be considered as a first approximation, aimed at a "reconnaissance by fire" of the problem undertaken. The first step, which will allow planning for the subsequent ones.

2. MATERIALS AND METHODS

2.1. MATERIALS

The composition of the mixes prepared is shown in Table 2.

Component	P45	P50	P55
cement CEM I 42.5 R	350	350	350
river sand (0–2 mm)	580	566	552
crushed granite (2–8 mm)	541	528	515
crushed granite (8–16 mm)	812	793	773
water	158	175	193
superplasticizer	1.8	—	—

TABLE 2. The composition of the tested concrete batches (in $kg\,m^{-3}$).

Portland cement CEM I 42.5 R according to EN 197-1:2011 [19] was used in the production of the concrete. River sand of 0–2 mm fraction was used as fine aggregate. The coarse aggregate consisted of two fractions of crushed granite: 2–8 mm and 8–16 mm mixed in a 40 : 60 mass ratio. Tap water was used as mixing water. Three concrete mixes were prepared with different w/c ratios of 0.45, 0.50, and 0.55. A superplasticiser based on modified phosphonates was used in the series with $w/c = 0.45$.

For the research, from each mix, six cubic specimens with 100 mm edges were prepared to test compressive strength after 28 days, two cubic specimens with 150 mm edges were prepared to test air permeability and three 100 mm $\times$ 100 mm $\times$ 500 mm prisms were prepared for monitoring the progress of carbonation. All the specimens were demoulded after two days and cured in water. The period of water curing of the specimens depended on their final destination. For the compressive strength test, the specimens were cured in water for 26 days, and for the concrete carbonation and further air permeability tests, the specimens were cured in water for 12 days and then aged in air under laboratory conditions.

2.2. TEST METHODS

The compressive strength testing was performed on six 100 mm cubic specimens after 28 days from forming. The test was performed in accordance with EN 12390-3:2019 [20] using a ToniTechnik Toni Pact II press with a maximum compressive force of 3000 kN. The rate of stress increase was maintained at $0.5\,MPa\,s^{-1}$, as required by the standard [20] for compressive strength testing. The results obtained from all specimens were averaged and the standard deviation was also calculated.

A Proceq Torrent instrument was used to test the air permeability. Eight results were obtained per test run for each batch of concrete, corresponding to the air permeability measured on the four side walls of

two 150 mm cubic specimens. The instrument head was positioned as close as possible to the centre of each measured side. The position was fixed before the first test to avoid excessive voids in the concrete surface where the head gaskets adhere, which could give erroneous results. A minimum margin of 20 mm was also maintained between the edges of the measured surface and the head for the same purpose. Before applying the head to the surface to be tested, the local moisture content of the concrete was determined using a CMEXpert II meter. In order to obtain a more accurate result, four moisture measurements were taken on each wall, with a 90° horizontal turn of the position of the instrument after each reading. The first measurement of the air permeability of the concrete was carried out 54 days after the concrete mix had been prepared, and the specimens were placed in the CO_2 chamber for the first time after a further seven days.

Accelerated carbonation of the concrete was carried out in a special climate chamber. The chamber was equipped with instrumentation to maintain a set temperature, humidity and CO_2 concentration. These parameters were set at 20 °C, 60 % and 1 %, respectively. A carbonation cycle for one series lasted 6 weeks, of which the specimens were in the chamber for two weeks and then stored under laboratory conditions for the remaining four weeks to stabilise the humidity. The air permeability test was carried out 3 weeks after the specimens had been removed from the chamber for a given cycle.

To determine the theoretical value of air permeability as a function of moisture content according to Torrent, the moisture content and kT factor were also measured before the first carbonation cycle. From these initial measurements, the value of $kT_{5,t}$ was determined according to Equation (1). The theoretical value of $kT_{m,t}$ for specimens not subjected to carbonation was then determined from the results of the concrete moisture test in subsequent cycles according to Equation (2).

$$kT_{5,t} = kT_{m,m} \cdot e^{1.45(m-5)}, \tag{1}$$

$$kT_{m,t} = kT_{5,t} \,/\, e^{-1.45(m-5)}, \tag{2}$$

where:

- m ... measured moisture content of concrete (in %),
- $kT_{m,m}$ ... measured air permeability of concrete with moisture content equal to m % (before carbonation),
- $kT_{5,t}$ ... theoretical air permeability of concrete with moisture content equal to 5 %,
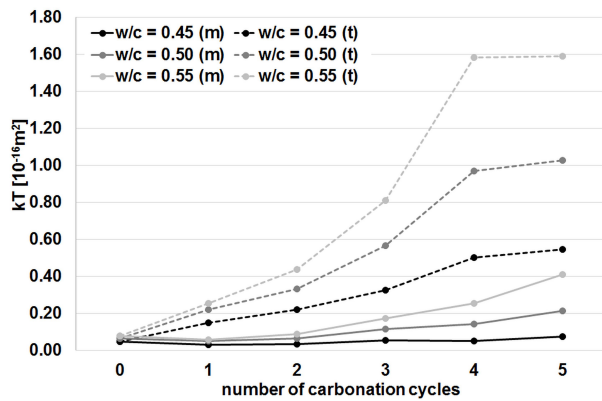- $kT_{5,m}$ ... theoretical air permeability of concrete with moisture content equal to m %.

FIGURE 1. Values of kT after specified number of carbonation cycles - (m) denotes the measured value and (t) the theoretical values calculated with use of Equation (2).

FIGURE 2. Values of kT in relation to concrete humidity - (m) denotes the measured value and (t) the theoretical values calculated with use of Equation (2).

3. RESULTS AND DISCUSSION

The results of the compressive strength test are given in Table 3. These are the mean values from the six tests. The standard deviations of the strength values are also given in the table.

Parameter	P45	P50	P55
compressive strength [MPa]	61.6	49.4	37.7
standard deviation [MPa]	2.5	2.3	2.1

TABLE 3. The results of the compressive strength test.

The compressive strength values obtained differ significantly from each other and, as expected, are negatively correlated with the w/c ratio values. The low values of standard deviation are characteristic for results obtained under laboratory conditions.

Figures 1 and 2 show the results of the air permeability test. In Figure 1, the continuous lines link the results obtained for each series after successive carbonation cycles. The dashed lines are assigned to the values of the kT coefficient calculated using Equation (2).

The figure also shows the initial air permeability values measured before the specimens were placed in the carbonation chamber. They are the common starting points for the plots of the measured and the theoretical values for each series. No moisture correction was applied to the initial kT values as there are no theoretical values necessary in cycle 0 (no carbonation).

Figures 1 shows that the difference between the theoretical and the measured values appears already after the first carbonation cycle and increases significantly after each subsequent cycle up to the fourth cycle. The difference after the fifth carbonation cycle increases only in the case of concrete with $w/c = 0.45$ and decreases slightly for the other two concrete batches.

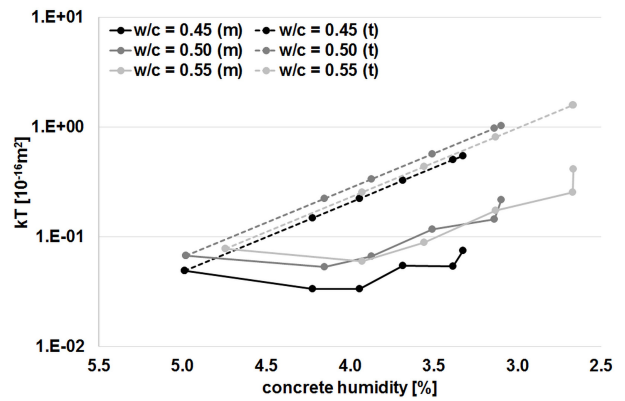Figures 2 shows the values of the kT coefficient as a function of the measured moisture content of the concrete at the time of testing. As in Figures 1, the solid lines correspond to the measured values of the kT coefficient and the dashed lines correspond to the theoretical values calculated from Equation (2). The graph in this form additionally illustrates the dynamics of the moisture content changes between successive testing cycles. It can be observed on the x axis of the graph.

Due to the use of a logarithmic scale, the theoretical relationships in Figures 2 are in the form of straight lines, which makes it easier to visualise the qualitative differences between the theoretical and the measured values. However, for the same reason, the scale of the quantitative differences between the theoretical and measured values is distorted.

Figure 2 shows, more clearly than Figure 1, that the kT value decreases after the first carbonation cycle and starts to increase from the second cycle (except for the concrete with $w/c = 0.45$, for which the upward trend actually starts from the third cycle). On a logarithmic scale, this section of the graph, which shows a clear upward trend can be approximated by a straight line, indicating a similar nature of the increase in the air permeability coefficient kT with decreasing humidity as the theoretical relationship described by Equation (2).

Based on these similarities exponential functions were fitted to the relationships shown in Figure 2, which illustrate the change in the measured values of the kT coefficient, on cycles where a close to linear increasing trend is evident. The fitted functions are characterised by very high values of the coefficient of determination R^2 for concrete series with the w/c ratio of 0.55 and 0.50. They are 0.95 and 0.94, respectively. For the concrete series with the w/c ratio of 0.45 the fitting is slightly worse, with the R^2 value of 0.83.

The exponent values of the fitted functions are: -1.37, -1.21, and -0.84 for the concrete with the w/c of 0.55, 0.50 and 0.45, respectively. This indicates a similar pattern of change in the kT value of the concrete as a function of moisture content, at least from a certain point onwards. However, it is evident that
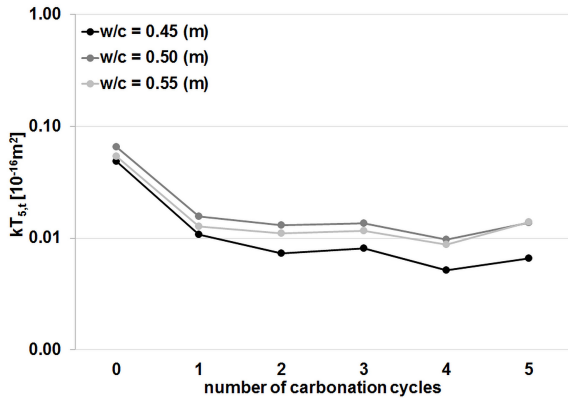
FIGURE 3. Measured values of kT converted for concrete of 5 % humidity using the Equation (1).

the rate of increase in the air permeability of concrete as the moisture content of the material decreases is not the same for all concrete series. Moreover, the rate increases with increasing values of the concrete's w/c ratio. This increase is not linear, but the small number of data (only three different w/c ratio values) makes it difficult to hypothesise about the nature of this relationship.

The trends in the change in air permeability of concrete as carbonation progresses are shown from a different angle in Figure 3. It shows the values of the kT coefficient converted for the same concrete moisture content of 5 %. The conversion was made using Equation (1).

The progression of the kT coefficient values in this figure can be divided into two parts. The first is the large decrease in air permeability through the concrete after the first carbonation cycle. The second part consists of the results obtained after subsequent carbonation cycles, where the graph flattens considerably. An attempt to fit a linear function to this part of the graph gave R^2 values of 0.64 (series with $w/c = 0.45$), 0.27 (series with $w/c = 0.50$) and 0.00 (series with $w/c = 0.55$). This indicates that as the w/c value increases, the effect of carbonation on the kT value decreases rapidly. The explanation for this is the change in porosity of the concrete. This occurs as the amount of water in the mix increases. The sealing effect of the carbonation process is reduced by the increased porosity and larger pore size.

Concerning the effect of the progress of carbonation on the air permeability of the concrete, this should reveal itself in the graph shown in Figure 2. The adopted methodology and plan of the research, combined with the trend of the decrease in the moisture content of the concrete after each carbonation cycle, should shape the dependence of the kT coefficient on the moisture content of the material in a specific way. It should deviate from a straight line, as the increase in air permeability of the concrete with a decrease in the pore moisture content should be partially compensated by a decrease in pore size. Consequently, the dependence of the kT coefficient on the moisture

content of the concrete should deviate downwards from the straight line determined solely by a decrease in this moisture content. However, if the influence of the concrete moisture content on the kT values is eliminated, the value of the kT coefficient should decrease after each successive carbonation cycle.

Such an effect can be seen in the graphs shown in Figure 2 (after excluding the results of the last cycle, which may be an artefact due to the jump in the absolute humidity of the ambient air) and in Figure 3. However, the effect is rather weakly outlined in Figure 2, which is most likely due to the fact that the rate of the decrease in concrete moisture is so high that the resulting increase in air permeability through the concrete is several times higher than its decrease due to the sealing of the concrete by carbonation. This suggests that consideration should be given to a method of testing for the effect of carbonation that significantly reduces the variability of concrete moisture during testing. The results in Figure 3 show somewhat more clearly a decreasing trend in kT as the carbonation progresses. However, this trend disappears completely for concrete with $w/c = 0.55$. It is most pronounced for concrete with $w/c = 0.45$.

4. CONCLUSIONS

The results of the research that was carried out led to the following conclusions:

1. The values of the air permeability coefficient of carbonated concrete obtained in the study are well below the theoretical values calculated from the relationship between the concrete moisture content and the kT coefficient developed for non-carbonated concrete.

2. It seems reasonable to conclude that the rate of change in the air permeability of concrete as a function of the change in its moisture content depends on the value of its w/c ratio.

3. Due to the significant influence of concrete moisture on the results of air permeability measurements, changes in the moisture content of the test material should be reduced to a minimum in further investigations.

4. As the w/c ratio value decreases, the effect of progressive carbonation is increasingly reflected in a decreasing kT value.

Notwithstanding the above conclusions, the research carried out indicates the need to further investigate the influence of the w/c ratio on the relationship between the moisture content of concrete and its air permeability. It also seems worth examining whether this relationship is not also significantly influenced by the amount and type of cement used in the concrete and the type of aggregate used, which affects the quality of the interfacial transition zone (ITZ) in the concrete.

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