In Situ Durability Characteristics of New and Old Concrete Structures

Guido Frenzer¹, Frank Jacobs² and Roberto J. Torrent³*

Abstract

This paper analyzes field experimental data obtained on about 30 concrete structures, both new (age up to 1 year) and old (age up to 60 years). The data include in situ non-destructive tests (NDT) of air-permeability $k_T$, electrical resistivity $\rho$ and surface moisture $m$, as well as tests conducted on drilled cores: $O_2$-permeability $k_O$, water sorptivity $a_{24}$, MIP, carbonation rate $K_c$ and chloride content $Cl$ at 10 to 20 mm depth. The main conclusions are that in situ $k_T$ of new structures is a good indicator of both $k_O$ and $a_{24}$. Regarding old structures, high values of $k_T$ and $k_O$ are accompanied by low $a_{24}$ values and by tight MIP pore structure. This phenomenon is attributed to microcracks, with strong effect on permeation but not so much on capillary suction. Similarly, high values of $k_T$ are not always accompanied by deep carbonation depths. The chloride content did not show correlation with either $k_T$ or $\rho$. In situ measurements of $\rho$, under the testing conditions, did not correlate with any other durability test. Finally, the spread of $k_T$ values for old structures is significantly wider than for young structures, suggesting that age improves durable concrete but weathering and damage impair non-durable concrete.

1. Introduction

Since 1990, the Swiss Federal Highway Administration (ASTRA) has been funding research projects aimed at studying the durability performance of new and old concrete structures by means of site testing (Torrent and Ebensperger 1993; Torrent and Frenzer 1995; Brühwiler et al. 2005; Jacobs 2006; Jacobs et al. 2009). The origin of these studies was an article (Menn 1987) written by one of the greatest Swiss bridge designers, late Prof. Christian Menn, asking for R&D projects oriented to reduce bridges maintenance costs by ensuring a better quality of their construction and maintenance. Top of the list of R&D topics proposed was ‘Characteristics and Measurement of the Permeability of the Cover Concrete’, preferably by non-destructive test (NDT) methods.

One positive result of such research efforts has been the introduction into the Swiss Standards of the need to check the ‘tightness’ of the cover concrete, or “Covercrete” (Newman 1987), on newly-built real structures (SIA 2013). For that purpose, a non-destructive test method, developed in the 90’s (Torrent 1992), to measure the coefficient of air-permeability of the Covercrete on site was standardized in 2003, updated in 2008 and more recently in 2019 as Annex E of SIA 262/1 (SIA 2019).

A second positive result was the collection of a significant amount of test results, obtained from several structures, both new and old, predominantly built in Switzerland.

In parallel, a large amount of data on pore structure, transport properties and durability tests (e.g. carbonation and chloride ingress), produced by many researchers in investigations made in the laboratory, typically on cast specimens, were compiled in state-of-the-art reports (RILEM 1995, 2007, 2015). However, it is well known that the quality of such specimens, designated as “Labcrete” (Newman 1987), is not representative of that achieved in the structure (“Realcrete”) and, more specifically, of that of the surface layers (Covercrete), strongly affected by the applied concreting practices (compaction, finishing, curing), by interaction with the environment and by microcracks. To have a more realistic picture of the quality of the Covercrete of real structures, vital for their durability, it is imperative to conduct site tests, which are more laborious, expensive and not always facilitated by the contractors or owners of the structures. These factors explain the relative scarcity of such site data. Yet, a comprehensive survey of several concrete structures in Japan was presented in (Imamoto et al. 2014), with data on site air-permeability and carbonation rate; in Switzerland, the air-permeability of some old bridges was also investigated (Ady et al. 1998).

The objective of this paper is to present and discuss the experimental results collected from comprehensive site tests conducted on several concrete structures, both new and old. The paper focuses on the relation between non-destructive site tests and several durability tests performed on cores drilled from the tested areas. The test results were obtained and reported by the authors at HMB (Holderbank Management u. Beratung AG, later Holcim Technology Ltd.) and at TFB (Technik und Forschung im Betonbau AG), both in Switzerland (Torrent and Frenzer 1995; Jacobs 2006). They had never been thoroughly and jointly analyzed in the past.

The authors believe that this comprehensive study

¹Plant Manager, Marti AG Solothurn, CH-3380 Walliswil bei Niederbipp, Switzerland.
²Senior Consultant, TFB AG, CH-5013 Wildegg, Switzerland.
³Technical Director, Materials Advanced Services Ltd., C1425ABV, Buenos Aires, Argentina. *Corresponding author, E-mail: torrent.concrete@gmail.com
provides valuable information on the usefulness and limitations of site testing, on the levels of quality that can be achieved in new structures and how and why this quality can change after decades of service. This information could be useful as well to those involved in the probabilistic modelling of service life of reinforced concrete structures.

2. Structures investigated

The data reported in this paper were collected on a large number of new and old structures. The sample of investigated structures comprise: 17 new structures (with ages at the time of testing between 18 and about 400 days) and 12 older structures (with ages at the time of testing between 17 and 60 years). The results of the investigations conducted by HMB and TFB were reported by Torrent and Frenzer (1995) and Jacobs (2006), respectively.

2.1 New structures

The two structures investigated by HMB were Bözberg highway Tunnel and Schaffhausen Bridge over the Rhine River (Torrent 1999). In both cases, tests were conducted on laboratory slabs (360 × 250 × 120 mm), cast with fresh concrete samples taken from trucks sent to the jobsite and, in parallel, in situ, in the areas where the same batches were placed. In the case of the bridge, as core drilling was forbidden, 1 m cubes were cast and kept close to the real elements they represented, to be sent to HMB laboratory for testing. In Bözberg Tunnel, a single mix was tested (OPC concrete, cube strength at 28 days = 50.5 MPa), whilst in Schaffhausen Bridge, two mixes were tested. One of them, used for the Deck was made with OPC and had a 28-day cube compressive strength of 51.1 MPa; the other, used for the Pylon, was made with a cement containing 8% Silica Fume having a 28-day cube compressive strength of 79.6 MPa.

The three old structures investigated by HMB correspond to bridges. Two bridges are located along Motorway N1 (today A1), linking the cities of Zürich and Bern, near the towns of Oensingen (where the underside of the deck was investigated) and of Rothrist (where the walls of Underpass Z64 were investigated). The third bridge is the Gärtnerstrasse Bridge, in the city of Basel, over the Wiese River (where the underside of the deck was investigated, but also its upper side, after removal of the asphalt overlay during maintenance operations).

The eight structures investigated by TFB correspond to one retaining wall along a motorway, four motorway bridges, two motorway tunnels and one building for housing. The concrete compositions are not known. At the time of construction usually OPC with a w/c ratio less than 0.50 (motorway structures) and approx. 0.60 (inner walls for building) and a maximum grain size of 32 mm were used.

3. Tests performed on the structures

3.1 In situ non-destructive tests (NDTs)

The following NDT methods were applied directly on the surface of the structural elements, typically without any previous preparation.

(a) Air-permeability $k_T$ (m²), (Torrent test method) described in Annex E of Swiss Standard (SIA 2019); the first version of the standard was issued in 2003.

(b) Surface electrical resistivity $\rho$ (kΩ·cm), (Wenner test method), guidelines in (Polder 2000). Both $k_T$ and $\rho$ were measured using the Torrent Permeability Tester instrument (Proceq). It is worth mentioning that $\rho$ was measured with the intention of assessing the moisture conditions of the surface at the moment of measuring $k_T$; hence, both properties were measured at the prevailing temperature and moisture conditions at the moment of test, without any effort to artificially wet or dry the surface.

(c) Surface moisture content $m$ (%), electrical impedance method, using a Tranex Concrete Encounter device.

3.2 Semi-destructive tests applied on drilled cores

The following tests were applied in the laboratory, on drilled cores saw-cut to size:

(a) O₂-permeability $k_O$ (m²), according to the RILEM-Cembureau test method (RILEM 1999), measured on $\Omega 100 \times 50$ mm discs, conditioned by 6 days oven drying at 50°C, followed by 1-day cooling to 20°C in a desiccator. The reported value is the average of the results obtained under relative applied pressures of 0.5 and 2.5 bar.

(b) Water sorptivity $a_24$ (g/m²/s⁰.⁵), HMB procedure, was obtained by placing the same discs used for $k_O$ in contact with 3 mm of water and monitoring the mass increase due to capillary suction, along the lines of Annex A of the Swiss Standard SIA 262/1 (SIA 2019).
The mass of water absorbed per unit surface area of the specimen (g/m²), after 24 hours of contact, divided by the square root of 24 hours (s¹) is the water sorptivity \( a_{24} \).

(c) Water sorptivity \( a_{24} \) (g/m²/s¹), TFB reported values, was obtained on Ø50 × 50 mm discs, conditioned by 2 days oven drying at 50°C, followed by 1-day cooling to 20°C in a desiccator. The values originally reported were of the so-called “Water conductivity” \( q_w \) (g/m²/h), after Annex A of Swiss Standard SIA 262/1 (SIA 2019). For comparison with HMB results, the \( q_w \) values were converted into \( a_{24} \) values through Eq. (1), developed at TFB from regression analysis of many test data:

\[
a_{24} = 3.4 + 1.142 (q_w - 2.26)
\]

where \( q_w \) in (g/m²/h) and \( a_{24} \) in (g/m²/s¹).

(d) Pore characteristics, from MIP analysis of diamond-cut small specimens, about 10 × 20 × 40 mm each, that could fit into the MIP analyser (Carlo Erba Series 2000 WS with macropore unit 120), capable of measuring pore radii between 3.7 and 300 000 nm. The samples were saw-cut from the exposed surface so as to penetrate 40 mm into the Covercrete, with all surfaces open to Hg intrusion. Four individual samples were tested for MIP from each tested surface. The reported values are the total porosity \( V_t \) (%) (median of the four values indicated by the instrument) and a ‘mean’ pore radius \( r_p \) (nm) (median of the four values indicated by the instrument). The reported values of \( r_p \) are close to the threshold pore radius, calculated as the peak of the derivative of intruded volume with the logarithm of pore radius.

(e) Carbonation rate \( k_c \) (mm/y²), based on the measurement of the carbonation depth \( X_c \) (mm) by the phenolphthalein method, on freshly exposed surfaces of cores drilled from old structures, divided by the square root of the age (years) of the structure.

(f) Chloride content \( C_l \) (% of cement weight), obtained by titration analysis of a 10 mm-thick slice saw-cut at 10 to 20 mm from the surface of a drilled core.

(g) Compressive strength \( f'_{c28} \) in MPa, measured on Ø100 × 100 mm cores drilled from old structures. The reported compressive strength results for new structures correspond to tests on 120 or 150 mm cubes, moist-cured during 28 days \( (f'_{c28}) \).

4. Experimental results

4.1 New structures

Tables A.1 and A.2 of the Annex present the test results obtained by HMB in Bözberg Tunnel and Schaffhausen Bridge, respectively, whilst Table A.3 presents the test results obtained by TFB in the 15 structures they investigated. To be remarked is that HMB results correspond to individual measurements made in situ or on cores drilled from the same location, whilst TFB results are statistical values, calculated from several individual values obtained for each element.

Except for \( kT \), the central values reported are the averages of the individual values obtained (e.g. \( \rho_{avg} \) and \( m_{avg} \) for electrical resistivity and surface moisture, respectively) and the scatter is their standard deviation (e.g. \( s_p \) for resistivity).

Regarding air-permeability \( kT \), that is best represented by a log-normal distribution (Conciatori 2005; Denarié et al. 2005; Jacobs and Hunkeler 2006; Misák et al. 2008), the central value is given by \( kT_{gm} \), which is the geometric mean of the individual \( kT \) values and the scatter by \( s_{LOG} \), that is the standard deviation of the log₁₀ of the individual \( kT \) values (Jacobs 2006).

4.2 Old structures

Tables A.4 to A.6 of the Annex present the test results obtained by HMB on Oensingen Bridge (30 years old), Underpass Z64 (20 years) and Gärnterstrasse Bridge in Basel (60 years), respectively. Table A.7 presents the results obtained by TFB in the 8 structures investigated. It was not possible to identify the cement type used in the old structures investigated, hence all are identified by the code “0” as per the classification in Section 2.1. Most likely, these structures were built with OPC; strongly predominant in Switzerland by the time of their construction.

4.3 Laboratory results

Test results obtained on laboratory cast specimens kept 21 days in a dry room (20°C, 50% RH) after 0, 7, or 28 days moist curing, reported in Tables 3.1-III and 3.2-IV of the study by Torrent and Ebensperger (1993) and in Tables 1.2.1.1, 1.2.1.2 and 3.2.1.1 of that by Torrent and Frenzer (1995), are often included in the analysis of the site data, as reference.

It is worth mentioning that interesting laboratory and site test results of MIP parameters (threshold pore radius and total pore volume) have been reported (Sakai et al. 2013, 2014), showing close relationships between them and both \( kT \) and water permeability. Another attempt to relate air-permeability and carbonation with the microstructure of cement paste (investigated by SEM-EDX) was reported by Jeon et al. (2012).

5. Analysis of the results

The figures included in this chapter refer to N (New Structures) and O (Old Structures), followed by a number between 0 and 5, corresponding to the cement type classification presented in Section 4.1. The data for new structures were taken from Tables A.1 to A.3 and for the Old Structures from Tables A.4 to A.6, indicated in some legends.

5.1 Relation in situ tests vs. strength

Figure 1 presents the relation between the in situ coefficient of air-permeability \( kT \) and cube compressive strength \( f'_{c28} \) of new structures and core compressive
strength $f'_{c}$ of old structures. The dashed line represents the relation between gas permeability $K_{g}$ and cube compressive strength $f'_{c28cyl}$ converted from cylinder strength using the conversion by L'Hermite (1997), which is Eq. 5.1-123 in *fib* Model Code 2010 (*fib* 2012). This equation is meant for tests on laboratory samples. Figure 2 is similar but for *in situ* electrical resistivity $\rho$ in abscissa.

Figure 1 shows that the results obtained on new structures do not depart significantly from the *fib* predictions (dotted line), although some results show, for the same strength, higher $kT$ values than the predicted ones. This may reflect the loss of quality of the cover concrete (evaluated *in situ* by $kT$), compared with that obtained on laboratory specimens, something noticeable in Tables A.1 and A.2 and discussed by Torrent (1999).

Regarding old structures, the first aspect to remark from Fig. 1 is the relatively high core strengths obtained (values typically between 40 and 100 MPa). However, these high strengths are not always accompanied by equally low permeability $kT$; the points departing even farther from the *fib* prediction dotted line. Indeed, high permeabilities ($kT > 1.0 \times 10^{-16}$ m²) were measured on old structures, even when the core strength $f'_{c}$ was in the range 40 to 75 MPa. As discussed later, this is attributed to deterioration of the Covercrete due to weathering, applied loads and, often, to microcracking.

Yet, an expected trend of higher site $kT$ for lower core strength $f'_{c}$ can be observed for old structures; the difference is that, in the former, the core strength reflects better the quality of the in-place concrete than the cast cubes.

Figure 2 shows that no clear relationship exists between $f'_{c28}$ and $\rho$, tested on site. One reason for the missing trend is, that, in new structures a large variety of cement types was used and the cement type influences resistivity much more than strength. For instance, three out of the four structures built with a silica fume-containing cement (diamond symbols) show high values of $\rho$, confirming the effect silica fume has in raising the electrical resistivity. RILEM recommendations (Polder 2000) indicate that the electrical resistivity of concretes made with blast furnace slag (> 65% slag) or fly ash (> 25%) or silica fume (> 5%) is about 5 times higher than for those made with OPC. In the case of Fig. 2, the expected trend of higher site resistivity $\rho$ for higher core strength $f'_{c}$, cannot be observed.

The relation between electrical resistivity and compressive strength was studied by Ramezanianpour et al. (2011) in a comprehensive laboratory investigation involving 57 mixes made with nine different binders. The correlation was very good ($R^2 = 0.87$ approx.) when applied to mixes made with the same binder, but turned rather poor ($R^2 = 0.41$) when all binders were included. In the case of Fig. 2, the results shown correspond to field data of both strength and $\rho$. It is therefore important to have in mind the many factors that can influence the $\rho$ readings, on top of that of the cement type, already discussed. One of the most comprehensive analysis of these factors was made by Azarsa and Gupta (2017), identifying w/c ratio, temperature and moisture of the concrete, vicinity of rebars and the presence of cracks as important factors influencing the results. To those factors, Thomas et al. (2013) add the pore structure and the composition of the pore solution (related to the cement type and w/c ratio), carbonation and contamination with chlorides. The effect of temperature was studied by Coyle et al. (2016) who reported that $\rho$ is reduced by factor of 3 when the temperature increases from 5 to 30°C. The strong effect of moisture and moisture gradients on $\rho$ was thoroughly investigated by Minagawa et al. (2017), whilst the role of reinforcement on $\rho$ was dealt with by Angst and Elsener (2014) and by Salehi et al. (2016). Improving the conditions for site measurement of the electrical resistivity $\rho$ as, for instance, by trying to saturate the concrete surface, is far from easy Presuel-Moreno et al. (2010).

This myriad of factors affecting field test results of $\rho$ can explain the recorded lack of correlation in Fig. 2.

### 5.2 Relation between *in situ* tests

Figure 3 presents the relation between air-permeability $kT$ and electrical resistivity $\rho$, both measured on site on new and old structures, at the temperature and moisture conditions prevailing at the moment of test. It can be seen that both variables show no dependence from each other, contrary to the expected decreasing relation of $\rho$ with increasing $kT$. Here again, the factors discussed in connection with Figs. 1 and 2, apply.
5.3 Relation between in situ and laboratory tests

Figures 4 to 7 present the relation between the air-permeability $k_T$ and $k_O$, $a_{24}$, $r_p$, and $V_t$, respectively, for new and old structures. $k_T$ was measured on site and the other four properties on samples cut from cores drilled from the same locations. The Annex tables containing the data are indicated. As reference, the values obtained in the laboratory, under the conditions described in Section 4.3, are also plotted.

Figure 4 shows that the coefficient of air-permeability $k_T$, measured in situ on new and old structures, correlate reasonably well with the coefficient of $O_2$-permeability $k_O$, measured in the lab on preconditioned cores drilled (at the same place) from the same structures. Most interesting, the relation obtained on new and old structures fits quite well to that obtained on specimens, cast, cured, preconditioned and tested in the laboratory. It is worth remarking that the $k_T$ values obtained on Oensingen bridge (O-A.4) span five orders of magnitude. The scatter can be explained by the different degrees of saturation and different volumes of Covercrete investigated, $k_T$ exploring a Ø50 mm cylinder of variable length (typically between 5 and 100 mm, depending on the permeability) whilst $k_O$ explores a Ø150 mm × 50 mm thick cylinder.

Figure 5 shows a rather different picture. The water sorptivity $a_{24}$ of new structures is significantly higher, for the same in situ $k_T$, than that obtained on old structures; moreover, the results on new structures fit quite well the relation obtained on laboratory specimens. The water sorptivity $a_{24}$ of old structures is less than half the value obtained on laboratory specimens for the same $k_T$, especially noticeably for $k_T$ values above $0.1 \times 10^{-16} \text{ m}^2$. The following effects can contribute to this phenomenon: a) the carbonation of old structures has a stronger effect on the capillary suction than on gas-permeability; b) high permeability values of $k_T$ in old structures, after years of weathering, are due to the appearance of microcracks in the ITZ and/or matrix, that have a stronger effect on gas permeability than on capillary suction; c) the different penetration of the tests into the Covercrete and d) some possible effect of moisture on $k_T$, eliminated by oven-drying for $a_{24}$.
Figures 6 and 7 throw some light on the previous discussion. They present the relation of \( kT \) with mean pore radius \( r_p \) and with total porosity \( V_t \), respectively, for new and old structures. Results obtained on laboratory specimens are also included for reference purposes. It can be seen that the pore structure (determined by MIP) of old concretes of permeability \( kT \) above \( 0.1 \times 10^{-16} \text{ m}^2 \) is much tighter (lower radius \( r_p \) and total porosity \( V_t \)) than what would be expected from testing laboratory specimens. Since the MIP test results plotted in Figs. 6 and 7 correspond to the non-carbonated zone, the effect of carbonation has to be excluded. Actually, as expected, the pore structure of the carbonated zone is even tighter, see few MIP results in Table A.4.

Figures 8 and 9 also help in the clarification of the above discussion. They show the relation between the water sorptivity \( a_{24} \) and the mean pore radius \( r_p \) and total porosity \( V_t \), respectively, for few new and old structures, as well as for laboratory tests on cast specimens. We can see that, contrary to the relation \( kT \) vs pore structure (Figs. 6 and 7), the \( a_{24} \) results obtained on the new and old structures fit quite well to those obtained on laboratory specimens.

The analysis of the data presented in Figs. 5 to 9 indicates that the microstructure of the concrete in the old structures remains quite tight (low \( r_p \) and \( V_t \) values) after decades of exposure to the mildly severe Swiss climate (that yet includes frost-thaw cycles and de-icing salts for bridges and tunnels). The very high air- and \( \text{O}_2 \)-permeabilities \((kT) \) of the old concretes can then be attributed to defects (bond or matrix microcracks) that facilitate the flow of gas under pressure, but that do not influence so much capillary suction (relatively low \( a_{24} \)).

No clear relation was found between the electrical resistivity \( \rho \) and microstructural \((r_p \) and \( V_t \)) or transport parameters \((a_{24} \) and \( kO \)), same as shown in Fig. 3 with site permeability \( kT \). For the sake of brevity, just the relation between \( a_{24} \) and \( \rho \) is shown in Fig. 10, where the expected trend of higher \( a_{24} \) for lower \( \rho \) is not apparent. Since the main focus of the investigations here reported was on air-permeability \( kT \) testing, the conditions under which the electrical resistivity \( \rho \) was measured (avoiding rainy or wet weather, variable temperatures, vicinity of steel) were not ideal for the latter. Additionally, resistivity is more strongly influenced by the cement type than the pore size distribution. This was the reason, too, to prescribe in the Swiss Standard SIA 262/1 (SIA 2019) the measurement of the surface moisture \( m \) by an electrical impedance-based instrument, abandoned the resistivity as originally recommended (Torrent and Frenzer 1995; Jacobs et al. 2009).

5.4 Relation between in situ tests and durability performance of old structures

As described in Section 3.2, in several old concrete structures, the carbonation rate \( K_c \) was determined and, in some of them, also the chloride content \( C_I \) in a 10 to 20 mm deep slice, cut from drilled cores. Figure 11 presents the relation of \( K_c \) with the site measurement of \( kT \) (the white triangles correspond to Basel bridge deck that was covered with asphalt in service which, logically, yielded \( K_c = 0 \)).

Figure 11 shows a trend observed also in structures tested in Japan and Portugal (Imamoto et al. 2016), of which use was made to assess the service life of Port of Miami Tunnel (Torrent et al. 2013). It indicates that, for very low \( kT \) values (below \( 0.01 \times 10^{-16} \text{ m}^2 \)), the carbonation rate \( K_c \) is negligible and that, for low \( kT \) values (between \( 0.01 \times 10^{-16} \text{ m}^2 \) and \( 0.1 \times 10^{-16} \text{ m}^2 \)) \( K_c \) is rather low (typically below \( 2.0 \text{ mm/y}^\frac{1}{2} \)). For higher \( kT \) values there is some uncertainty on the carbonation rate that was treated mathematically by Neves et al. (2018). This may be due to the already discussed presence of weathering.
microcracks that have a larger effect on $kT$ than on $K_c$, as already suggested by Imamoto et al. (2016).

Regarding chloride content $Cl$, no clear relation can be observed with either site air-permeability $kT$ (Fig. 12) or with site electrical resistivity $\rho$ (Fig. 13). This can be due to the fact that the chloride content near the surface depends not only on the transport properties of the Covercrete but also on the vicinity and intensity of the chloride sources. The penetration (by mix modes) of chloride ions from salty solutions in permanent or sporadic contact with the structure is very complex, due to the overlapping of several physical mechanisms (Hunkeler 2000). Chlorides may penetrate by permeation, carried by the saline water solution and, alternatively or complementary, by ion diffusion. Rain washout and evaporation, affecting predominantly the surface layers, add complication to the phenomenon.

In a separate investigation (Jacobs 2008) found a relation between $kT$ and the chloride content of 20 to 30 mm deep concrete slices for several columns of six 30 years old bridges crossing a Swiss motorway.

5.5 In situ $kT$ tests statistical distributions

Figure 14 shows the frequency distribution of the central value of $kT$ ($kT_{gm}$) obtained from new and old structures, whilst Fig. 15 shows the frequency distributions of the scatter of $kT$ values ($s_{LOG}$). The number of cases analyzed for new and old structures amounts to 35 each.

Although the results were not obtained at young and later ages on exactly the same structures, some patterns can be observed. First, the histogram of $kT_{gm}$ values (Fig. 14) of new structures spans 5 class intervals, whilst that of old structures spans 9 class intervals. This may be attributed, a bit speculatively, to a phenomenon by which concrete that is originally of “good” quality (low $kT_{gm}$) and durable becomes better with the passage of time, whilst concrete that is originally of insufficient quality (high $kT_{gm}$) impairs after decades of service and weathering exposure.

The same reason can explain why the scatter of $kT$ ($s_{LOG}$) within each element tested tends to be larger for old structures compared with new structures (Fig. 15).

6. Conclusions

Based on the analysis of the experimental results of this
The authors believe that more research efforts should be placed on investigating the characteristics of the concrete in real structures, their spatial variability, and the phenomena involved in their evolution with age, something that is unlikely to be mimicked in the laboratory. This would help in making prediction models (e.g. for carbonation or chloride ingress) more realistic and reliable.

Additionally, quality control through testing specimens cast with the delivered concrete are specified in detail in concrete standards [e.g. SN EN 206 (2013)], but quality control in situ by testing the structure is mostly missing. NDTs and/or drilling and investigating cores from new structures are important to evaluate the true permeability and thickness of the Covercrete, to reassure the owner that the quality of the end-product required for reaching the design or expected service life of the structure has been achieved. This should be part of the birth-certificate documentation.

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Annex
Tables A.1 to A.7 show the test results obtained from the various structures.

Table A.1 Test results obtained by HMB on Bözberg Tunnel.

| Tested Truck | Laboratory Tests | Site Tests |
|--------------|------------------|------------|
|              | $kT$ 10^{-16} m² | $kO$ 10^{-16} m² | $a_{24}$ g/m²/s^½ | $\rho$ kΩ.cm | $kT$ 10^{-16} m² | $kO$ 10^{-16} m² | $a_{24}$ g/m²/s^½ | $\rho$ kΩ.cm | $r_p$ nm | $V_t$ % |
| M4           | 0.028            | 0.177      | 9.3       | 12.3 | 0.113 | 0.374      | 9.1       | 7.6       | 34  | 9.1 |
| M5           | 0.083            | 0.142      | 7.9       | 11.3 | 0.154 | 0.321      | 9         | 9.6       | 36  | 6.9 |
| M7           | 0.008            | 0.161      | 9.6       | 12.8 | 0.059 | 0.26       | 9.6       | 33  | 7.4 |
| M8           | 0.081            | 0.357      | 9.4       | 12.2 | 0.111 | 9.1        | 9.6       | 6.9       | 33  | 7.4 |
| M9           | 0.008            | 0.156      | 8.4       | 14.3 | 0.005 | 0.161      | 7.7       | 9         | 33  | 7.4 |
| M10          | 0.025            | 0.126      | 8.2       | 14.2 | 0.015 | 9.1        | 7.1       | 33  | 7.4 |
| N            | 6                | 6          | 6         | 6    | 6     | 4          | 4         | 6    | 6   |
|              | **Central**      |            | **Scatter** | 0.026 | 0.187 | 8.8       | 12.9      | 0.045 | 0.279 | 8.7 | 8.9 |
|              | 0.45             | 0.085      | 0.7       | 1.2  | 0.59  | 0.091      | 0.7       | 1.3   |      |     |

Table A.2 Test results obtained by HMB on Schaffhausen Bridge.

| Pylon | Test Point | $kT$ 10^{-16} m² | $kO$ 10^{-16} m² | $a_{24}$ g/m²/s^½ | $\rho$ kΩ.cm | $r_p$ nm | $V_t$ % |
|-------|------------|------------------|------------------|-------------------|--------------|---------|-------|
| Lab   | 2 slabs    | 0.002            | 39.3             | 0.071             | 3.3          | ---     | ---   |
|       | 1-1        | 0.027            | 9.4              | 0.097             | 4.1          | ---     | ---   |
|       | 1-2        | 0.034            | 8.8              | 0.115             | 3.2          | ---     | ---   |
|       | 1-3        | 0.016            | 14.1             | 0.176             | 3.7          | ---     | ---   |
|       | 1-4        | 0.008            | 20.9             | 0.116             | 3.7          | ---     | ---   |
|       | 2-1        | 0.003            | 14.1             | 0.089             | 3.3          | 25      | 4.9   |
|       | 2-2        | 0.011            | 18.5             | 0.124             | 3.6          | ---     | ---   |
|       | 2-3        | 0.003            | 16               | 0.166             | 3.4          | ---     | ---   |
|       | 2-4        | 0.019            | 18.1             | 0.118             | 3.5          | 25      | 6.5   |
| Cubes | 1+2        | **N** 9          | **N** 9          | **N** 9           | **N** 9     | **N** 9 | **N** 9 |
|       | **Central**| 0.009            | 16.8             | 0.119             | 3.5          | ---     | ---   |
|       | **Scatter**| 0.45             | 9                | 0.034             | 0.3          | ---     | ---   |
| On Site| **N** 23  | **N** 23         | **N** 23         | **N** 23          | **N** 23    | **N** 23 | **N** 23 |
|       | **Central**| 0.041            | 41.4             | ---               | ---         | ---     | ---   |
|       | **Scatter**| 0.27             | 16.9             | ---               | ---         | ---     | ---   |

Table A.3 Test results obtained by HMB on Schaffhausen Bridge.

| Deck | Test Point | $kT$ 10^{-16} m² | $kO$ 10^{-16} m² | $a_{24}$ g/m²/s^½ | $\rho$ kΩ.cm | $r_p$ nm | $V_t$ % |
|------|------------|------------------|------------------|-------------------|--------------|---------|-------|
| Lab  | 2 slabs    | 0.017            | 7.4              | 0.144             | 6.7          | ---     | ---   |
|      | 3-1        | 0.011            | 5.4              | 0.218             | 8.2          | ---     | ---   |
|      | 3-2        | 0.016            | 4.3              | 0.189             | 8.8          | ---     | ---   |
|      | 3-3        | 0.008            | 5.2              | 0.175             | 7.6          | ---     | ---   |
|      | 3-4        | 0.02             | 7.5              | 0.207             | 6.7          | ---     | ---   |
| Cubes| 3+4        | **N** 9          | **N** 9          | **N** 9           | **N** 9     | **N** 9 | **N** 9 |
|      | **Central**| 0.017            | 6.2              | 0.22              | 7.4          | ---     | ---   |
|      | **Scatter**| 0.48             | 1.2              | 0.066             | 0.8          | ---     | ---   |
| On Site| **N** 10  | **N** 10         | **N** 10         | **N** 10          | **N** 10    | **N** 10 | **N** 10 |
|      | **Central**| 0.074            | 7.9              | ---               | ---         | ---     | ---   |
|      | **Scatter**| 0.68             | 0.7              | ---               | ---         | ---     | ---   |
Table A.3 Test results obtained by TFB on 15 new structures.
(The superscripts varying from 0 to 5 indicate the types and classes of cement used, as explained in Section 2.1)

| Structure         | Elements Tested | N  | $kT_{gm}$ | $s_{LOG}$ | $\rho_{avg}$ | $s_{\rho}$ | $m_{avg}$ | Age | $f'c_{28}$ |
|-------------------|-----------------|----|-----------|-----------|--------------|------------|-----------|-----|------------|
| Bridge 1 Box girder$^0$ | Wall            | 4  | 0.093     | 0.32      | 20 4        | 5.6        |           |     |            |
|                   | Under. Deck     | 6  | 0.497     | 0.42      | 54 16       | 5.1        | 179 58    |     |            |
|                   | Floor           | 4  | 1.00      | 0.68      | 33 2        | 3.9        |           |     |            |
| Bridge 2$^0$      | Underside Deck  | 8  | 1.221     | 0.44      | 69 6        | 5.1        | 162 54.5  |     |            |
| Abutment Wall     | Inner Side      | 6  | 0.115     | 0.55      | 43 11       | 5.4        | 246 54    |     |            |
|                   | Outer Side      | 5  | 1.261     | 0.23      | --- 5       | ---        |           |     |            |
| Bridge 4$^1$      | Pillar 0-1 m    | 9  | 0.122     | 0.35      | 35 13       | 4.3        | 192 46    |     |            |
|                   | Pillar 1 - 3.4 m| 3  | 0.244     | 0.47      | 31 16       | 4.3        |           |     |            |
| Bridge 5 Guide Wall | Element 44$^0$  | 3  | 0.3       | 0.22      | 11 2        | 18         | ---       |     |            |
|                   | Element 6$^5$   | 3  | 0.123     | 0.30      | --- ---     | 277 51     |           |     |            |
|                   | Element 20$^5$  | 4  | 1.583     | 0.35      | 36 3        | 204 38     |           |     |            |
|                   | Element 12$^1$  | 5  | 0.351     | 0.61      | 10 3        | 259 58     |           |     |            |
| Building 1$^4$    | Wall Outer Side | 20 | 0.158     | 0.93      | 11 3        | 175 54.8   |           |     |            |
|                   | Wall Inner Side | 21 | 2.062     | 0.68      | 130 95      | 153 26.7   |           |     |            |
| Building 2$^0$    | Ceiling         | 10 | 0.401     | 0.76      | 33 1        | 182 37.7   |           |     |            |
|                   | Wall            | 16 | 0.26      | 0.76      | 28 4        | 182 36.5   |           |     |            |
| Building 3$^4$    | Wall            | 15 | 0.035     | 0.65      | 43 18       | 5.1        | 136 45    |     |            |
| Building 4$^0$    | Wall            | 15 | 0.292     | 0.57      | 40 5        | 1786 55$^*$|           |     |            |
| Stadium$^4$       | T-Beam Side A   | 18 | 0.269     | 0.75      | 26 27       | --- 286    | 45        |     |            |
|                   | T-Beam Side B   | 12 | 1.035     | 0.45      | 14 3        | ---        |           |     |            |
|                   | Walls D, E, F   | 15 | 0.659     | 0.49      | 40 13       | 4.5        | 404 57    |     |            |
|                   | Walls A, B, C   | 20 | 1.546     | 0.59      | 76 26       | 4.4        | 57        |     |            |
| Tunnel 2$^1$      | Wall            | 18 | 0.067     | 0.77      | 10 5        | 413 52     |           |     |            |
| Tunnel 3 Wall$^2$ | w/o microcrack  | 13 | 0.076     | 0.09      | --- ---     | 22 47      |           |     |            |
|                   | w/ microcrack   | 14 | 0.108     | 0.56      | 8 1        | ---        |           |     |            |
| Tunnel 4$^1$      | Dome            | 15 | 0.04      | 0.89      | 10 2 > 6.5  | ---        |           |     |            |
| Tunnel 5$^1$      | Dome            | 8  | 0.234     | 0.34      | 17 3 > 6.5  | ---        |           |     |            |
| Tunnel 6 Central Wall$^5$ | 40-41 | 5  | 0.118     | 0.19      | 75 3        | 4.4        | 63.1      |     |            |
|                   | 1000-1001       | 6  | 0.551     | 0.41      | 115 3       | 4          | 59.7      |     |            |
|                   | 1995-1996       | 6  | 0.554     | 0.87      | 115 3       | 4          | 64        |     |            |
|                   | 2598-2599       | 5  | 0.485     | 0.79      | 115 3       | 3.8        | 57.8      |     |            |
|                   | 3200-3201       | 5  | 0.166     | 0.34      | 85 3        | 4.2        | 63.5      |     |            |

| Sets              | 32 32 29 28 17 |   |           |            |             |           |     |            |
| Min               | 0.04 0.09 8 1 3.8 |   |           |            |             |           |     |            |
| Avg               | 0.5 0.53 46 10 4.6 |   |           |            |             |           |     |            |
| Max               | 2.06 0.93 130 95 >6.5 | # core |        |            |             |           |     |            |

* rebound
Table A.4 Test results obtained by HMB on deck underside of Oensingen Bridge.

| Elements Tested | Test # | $k_T$ | $r_T$ | $r_O$ | $a_{24}$ | $K_e$ | $r_p$ | $V_t$ | $V_f$ |
|-----------------|--------|-------|-------|-------|---------|-------|-------|-------|-------|
|                 |        | $10^{-16}$ m² | kΩ.cm | $10^{-16}$ m² | g/m²/s⁵⁵ | mm²y⁵⁵ | mm | mm | % | % |
| 1               | 0.417  | 22.6   | 2     | 4.4    | 2.19    |      | ---  | ---  | ---  | ---  |
|                 | 0.004  | 58.1   | 0.023 | 2.4    | 0.91    |      | ---  | ---  | ---  | ---  |
|                 | 0.046  | 119.4  | 0.099 | 4.5    | 0.91    |      | ---  | ---  | ---  | ---  |
|                 | 0.004  | 62.8   | 0.044 | 3.0    | 0.91    |      | ---  | ---  | ---  | ---  |
|                 | 3.23   | 62.8   | 0.546 | 7.9    | 3.65    | 43   | 35   | 6.7  | 4.5  |
| 2               | 0.085  | 56.6   | 0.527 | 4.5    | 1.83    | 38   | 5.2  |      |      |
|                 | 0.004  | 110    | 0.09  | 3.4    | 0.73    |      | ---  | ---  | ---  | ---  |
|                 | 0.004  | 47.1   | 0.076 | 3.2    | 0.73    |      | ---  | ---  | ---  | ---  |
|                 | 0.03   | 58.1   | 0.099 | 3.3    | 1.10    |      | ---  | ---  | ---  | ---  |
|                 | 0.03   | 20.4   | 0.089 | 4.3    | 0.73    |      | ---  | ---  | ---  | ---  |
|                 | 0.014  | 10.8   | 0.17  | 2.7    | 0.73    |      | ---  | ---  | ---  | ---  |
|                 | 0.007  | 22.6   | 0.117 | 3.1    | 0.37    |      | ---  | ---  | ---  | ---  |
|                 | 0.06   | 11.9   | 0.106 | 2.9    | 0.73    |      | ---  | ---  | ---  | ---  |
|                 | 0.03   | 28.3   | 0.029 | 1.9    | 0.37    |      | ---  | ---  | ---  | ---  |
|                 | 0.004  | 39.3   | 0.015 | 1.5    | 0.37    | 29   | 4.8  |      |      |
| 3               | 0.205  | 0.559  |       |       |         |      |      |      |      |
|                 | 0.205  | 0.16   |       |       |         |      |      |      |      |
|                 | 0.083  | 0.19   |       |       |         |      |      |      |      |
|                 | 3.57   | 0.474  |       |       |         |      |      |      |      |
|                 | 28.15  | 22.35  |       |       |         |      |      |      |      |
| N               | 30     | 30     | 30    | 30    |         |      |      |      |      |
| Central         | 0.128  | 50.5   | 1.9   | 4.5    | 1.2     |      |      |      |      |
| Scatter         | 1.28   | 38.8   | 4.8   | 1.9    | 1.1     |      |      |      |      |
| N               | 30     | 30     | 30    | 30    | 30      |      |      |      |      |

NC: Non-carbonated  
C: Carbonated

Table A.5 Test results obtained by HMB on walls of Underpass Z64.

| Element Tested | Test Position | $k_T$ | $k_O$ |
|----------------|---------------|-------|-------|
| Lateral Walls  |               | $10^{-16}$ m² | $10^{-16}$ m² |
| 1              | 0.205         | 0.559 |
| 2              | 0.205         | 0.16  |
| 3              | 0.083         | 0.19  |
| 4              | 3.57          | 0.474 |
| 5              | 28.15         | 22.35 |
| N              | 5             | 5     |
| Central        | 0.811         | 4.75  |
| Scatter        | 1.06          | 9.84  |

Table A.6 Test results obtained by HMB on the deck of Basel Bridge.

| Element Tested | Test Position | $k_T$ | $k_O$ | $K_e$ | $f_e'$ |
|----------------|---------------|-------|-------|-------|--------|
| Deck           | 1/u           | 43.36 | ---   | 5.87  | ---    |
| underside      | 2/u           | 0.266 | 0.22  | 0.26  | ---    |
| 3/u            | 4.58          | 3.739 | 3.55  | 42.9  | ---    |
| 4/u            | 2.37          | 1.09  | 3.42  | ---   | ---    |
| Deck           | 5/u           | 0.79  | 0.426 | 2.39  | ---    |
| top side       | 6/u           | 0.236 | 0.429 | 4.84  | ---    |
| 7/u            | 0.653         | 2.717 | 0     | ---   | ---    |
| 8/u            | 2.04          | 2.114 | 4.91  | ---   | ---    |
| Deck           | 9/u           | 0.188 | 0.11  | 0     | 60.7   |
| top side       | 3/o           | 0.469 | 0.073 | 0     | ---    |
| 5/o            | 0.127         | 1.952 | 0     | 83.2  | ---    |
| N              | 11            | 10    | 11    |      |        |
| Central        | 0.909         | 1.29  | 1.94  |      |        |
| Scatter        | 0.74          | 1.28  | 2.11  |      |        |
Table A.7 Test results obtained by TFB on 8 old structures.

| Structure          | Element Tested | N  | $kT_{gm} \times 10^{16}$ m$^3$ | $s_{Log}$ | $\rho$ | $m$ | Age years | $f'_c$ | $K_c$ | $C_l$ | $a_{24}$ |
|--------------------|----------------|----|--------------------------------|----------|------|-----|----------|------|------|------|---------|
| Retaining Wall     | 19 (cracked)   | 6  | 0.183                         | 1.16     | 68   | 4.1 | 30       |      |      |      |         |
|                    | 21             | 6  | 0.497                         | 0.42     | 49   | 5.1 |          |      |      |      |         |
|                    | 26             | 6  | 1                             | 0.68     | 432  | 3.9 |          |      |      |      |         |
| Bridge 10 Abutment | Side A         | 15 | 0.039                         | 0.81     | 25   | 6.1 | 117      | 1.42 | 0.90 | 3.4  |         |
|                    | Side H         | 7  | 0.028                         | 0.4      | 8    | 6.2 |          | 1.67 | 0.70 |      |         |
| Bridge 11          | Pilar 323 B    | 6  | 6.456                         | 0.54     | 364  | 4.7 | 56.5     | 2.18 | 1.00 | 7.9  |         |
|                    | Pilar 318 B    | 6  | 0.383                         | 0.62     | 718  | 3.7 |          | 0.87 | 0.22 |      |         |
|                    | Pilar 207 B    | 6  | 0.046                         | 0.32     | 999  | 3.7 | 95       | 0.17 | 0.20 | 2.4  |         |
|                    | Pilar 205 B    | 6  | 0.07                          | 0.53     | 255  | 4.0 |          | 2.09 | 0.59 |      |         |
|                    | Pilar 204 B    | 7  | 0.432                         | 1.29     | 294  | 4.2 |          | 0.7  | 0.59 |      |         |
|                    | Pilar 201 B    | 7  | 0.506                         | 0.44     | 248  | 4.4 |          | 4.26 | 0.58 |      |         |
|                    | Pilar 201 Z    | 7  | 0.027                         | 1.11     | 218  | 4.6 | 82.5     | 0.78 | 0.55 | 2.5  |         |
|                    | Pilar 204 Z    | 6  | 0.103                         | 0.7      | 178  | 4.2 | 82       | 1.13 | 0.74 | 3.2  |         |
|                    | Pilar 205 Z    | 6  | 0.157                         | 0.43     | 160  | 4.6 |          | 4.18 | 0.58 |      |         |
|                    | Pilar 207 Z    | 7  | 0.063                         | 0.49     | 215  | 4.1 | 77       | 0.52 | 0.52 | 3.2  |         |
|                    | Pilar 318 Z    | 6  | 0.03                          | 0.39     | 213  | 4.6 |          | 1.13 | 0.50 |      |         |
|                    | Pilar 323 Z    | 9  | 10.55                         | 0.7      | 141  | 4.7 | 67       | 2.18 | 0.82 | 7.7  |         |
| Bridge 12          | Pilar         | 5  | 0.904                         | 0.65     | 500  | 2.8 | 84       |      |      |      |         |
|                    | Pylon         | 5  | 0.662                         | 1.31     | 30   | 4.4 | 92       |      |      |      |         |
|                    | "Sails"       | 3  | 0.26                          | 0.59     | 21   | 4.4 | 74       |      |      |      |         |
| Bridge 13          | Wall          | 5  | 0.108                         | 0.36     | 144  | 4.3 | 63.4     | 1.37 | 0.08 | 3.8  |         |
|                    | Underside Deck| 5  | 0.01                          | 0.38     | 73   | 3.8 | 22.5     | 0.73 | 0.32 | 3.1  |         |
| Tunnel 10          | Wall F2       | 3  | 0.055                         | 0.42     | 300  | 3.1 | 100      | 0.67 | 0.24 | 3.9  |         |
|                    | Wall F3       | 3  | 0.036                         | 0.52     | 60   | 4.0 | 102      | 0.49 | 0.10 | 3.2  |         |
|                    | Wall F5       | 3  | 0.046                         | 0.32     | 144  | 4.1 | 91       | 2.26 | 1.30 | 4.0  |         |
|                    | Wall F4       | 3  | 0.052                         | 0.1      | 240  | 3.8 | 91       | 2.55 | 1.81 | 4.0  |         |
| Tunnel 11          | Block 2       | 4  | 7.184                         | 0.68     | 210  | --- |          | 3.27 | 0.30 | 7.8  |         |
|                    | Block 80      | 3  | 0.99                          | 0.13     | 500  | --- |          | 5.49 | 0.75 | 13.7 |         |
|                    | Block 413     | 5  | 5.549                         | 0.7      | 750  | --- |          | 73   | 5.70 | 0.20 |         |
| Building 10 Slabs over | 2nd basement floor | 2  | 10.293                        | 1.27     | ---  | 2.0 | 49       |      |      |      |         |
|                    | Ground Floor  | 5  | 8.531                         | 0.52     | ---  | 2.0 | 49       |      |      |      |         |
|                    | 1st basement floor | 3  | 1.492                         | 0.42     | ---  | 2.0 | 60       |      |      |      |         |

Sets: Min, Avg, Max

Min: 0.01, 0.10, 2.0
Avg: 1.77, 0.61, 261
Max: 10.55, 1.31, 999