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Closing Letter of RILEM TC 281-CCC: Carbonation of Concrete with Supplementary Cementitious Materials

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Abstract

The RILEM Technical Committee (TC) 281-CCC, on carbonation of concrete with supplementary cementitious materials (SCMs) was active from 2018 to 2024, bringing together over 120 members from different continents. The objective of the TC was to understand the mechanisms leading to carbonation and identify best practices for the assessment of carbonation resistance of blended cement concrete. The activities of the committee were carried out in five different working groups (WGs) centring on (i) effect of SCMs on natural and accelerated carbonation of blended cementitious materials, (ii) modelling of carbonation, (iii) effects of the combined action of load and carbonation, (iv) carbonation induced corrosion, and (v) carbonation of alkali-activated materials. These topics covered all critical aspects to reveal the connections between the mechanisms and factors leading to carbonation of binders and concrete with SCMs, the impact of carbonation in concrete performance and corrosion, and the suitability of existing testing methodologies for its evaluation. The scientific activities of the TC members led to the publication of a topical collection with nine articles in Materials and Structures and one article in RILEM Technical Letters. This included three critical review papers, six original research papers and one recommendation. In this Letter we provide an overview of the key findings linked to the WGs activities and present remaining research needs on the topic of carbonation of concrete with SCMs.

Keywords: Carbonation; Supplementary cementitious materials; Alkali-activated concrete; Interlaboratory testing; Standards; Corrosion.

1 Understanding the carbonation of blended cements

Blended cements, where Portland cement clinker is partially replaced by supplementary cementitious materials (SCMs), provide one of the most feasible and rapidly implementable solutions for reducing carbon dioxide emissions associated with concrete production [1]. However, lowering the clinker content can lead to an increasing risk of neutralisation of the concrete pore solution and potential reinforcement corrosion due to carbonation [2]. The first action of the RILEM TC 281-CCC was to conduct an extensive literature review, which elucidated the effect of numerous SCM characteristics, exposure environments and curing conditions on the carbonation mechanism, kinetics and structural alterations in cementitious systems containing SCMs [3]. The analysis revealed that carbonation of concrete with SCMs differs significantly from carbonation of concrete solely based on Portland cement (PC). This is a consequence of the differences in the hydrate phase assemblage and pore solution chemistry, as well as the pore structure and transport properties, when varying the binder composition, age and curing conditions of the concrete.

1.1 Factors influencing carbonation of blended cements

The main difference between the PC and PC+SCM systems is its phase assemblage, which in turn impacts the pore solution composition and pore structure (e.g. pore size and its interconnectivity), as it is expected that the amount of portlandite decreases at higher SCM replacement levels. This is a consequence of the lower amount of Portland clinker in the cement (which produces portlandite during its hydration) and the consumption of portlandite during the pozzolanic reaction [4]. Portlandite carbonation is the main contributor of released water during carbonation, which can modify the internal relative humidity, and usually leads to a reduction in pore size and total volume of meso- and macro- pores due to $CaCO_3$ precipitation [5]. Portlandite carbonation may furthermore be incomplete due to the covering of portlandite crystals by calcium carbonate [6]. With the reduced content of portlandite in SCM containing systems, carbonation will

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happen more rapidly in the main CO_2-binding phases, calcium silicate hydrate (C-S-H) in the case of using silica fume, and Al substituted calcium silicate hydrate (C-A-S-H) phases in the case of using granulated blast furnace slag, fly ashes, metakaolin and other Al-containing SCMs. Carbonation of these hydrates seems to be the main contributor to carbonation shrinkage, especially for low Ca/Si C(-A)-S-H and induces coarsening of pore structure upon carbonation, which leads to reduction of mechanical strength [7]. This is particularly critical as carbonation of concrete with SCM will lead to a reduction in pH, but also to a coarsening in pore structure, consequently reducing the ability of these materials to withstand other forms of degradation by chemical or physical attack.

Open questions remain regarding the role of secondary reaction products forming in blended cements with SCMs. For example, in the case of using blast furnace slag, it is expected that formation of Mg-Al layered double hydroxides takes place [8]. Such phases have the potential to improve carbonation resistance (e.g. observed in alkali-activated slag cements [9, 10]). It is largely unknown how formation of AFm and AFt phases, as well as zeolites present in some SCMs such as volcanic ashes, might influence carbonation performance. It is of great importance that future research efforts focus on determining how the phase assemblages in cementitious systems could be tailored to optimise CO_2 uptake capacities of different hydrated phases, while preserving concrete performance.

When analysing carbonation rates reported for pastes, mortars and concretes, it was not possible to identify a correlation between such values for a given type of cement or SCMs. This is somehow expected considering the pore structure differences induced when adding aggregates and reducing the paste content in the material, which in turn will modify their transport properties. Therefore, although conducting carbonation studies in mortar specimens can provide information for materials selection, carbonation rate results cannot be used to predict concrete performance.

The carbonation mechanism and reaction kinetics also depend on the saturation degree of the concrete and the carbonation exposure conditions (e.g. relative humidity (RH), moisture load, temperature, CO_2 partial pressure), which in turn influence the microstructural changes identified upon carbonation [11]. For instance, in the case of plain PC systems the importance of CO_2 concentrations in accelerated testing is well understood, and it has been suggested that the carbonation products forming when using > 3% CO_2 are not identical to those observed in naturally carbonated materials [12]. This is of particular importance as several national accelerated carbonation standards prescribe the use of CO_2 concentration beyond this value, which can lead to misleading results. The effect of temperature on carbonation is usually overlooked, particularly when evaluating carbonation under accelerated testing methods, as the majority of standard test methods have similar ranges of exposure temperatures.

A summary of the factors influencing carbonation performance of cementitious materials containing SCMs is shown in Table 1.

Table 1. Overview compiled by RILEM TC 281-CCC of the parameters influencing carbonation performance of cementitious materials with SCMs, based on existing literature. Where FA, SF, BFS and LS stand for fly ash, silica fume, blast furnace slag and limestone, respectively. Adapted from [3].

Parameter		**Carbonation coefficient**	
Name	**Range**	**Increase ↑ decrease ↓ similar →**	**By a factor**
w/b[a]	0.4 → 0.65	↑	> 2.0[b]– > 3.5[c]
w/$CaO_{reactive}$	0.4 → 0.9	↑	≈ 5
Type of SCM (for a replacement of 25 wt.% of PC), which affects the *CaO* content (FA, SF < BFS)	FA, SF → LS → BFS → PC	↓	≈ 2.3 (FA, SF), 1.9 (LS), 1.3 (BFS)
a/c[d]	change with factor 1.7 → 2.3	↑	1.1[b]–1.5[c]
Concrete	changed to mortar	→ ↑	1.2–1.3
	changed to paste	↑	1.6–2.3
Coarse aggregate replaced by recycled aggregate		↑↓	< 1.0-2.0
Fine aggregate replaced by recycled aggregate		↑	3.75[b]–12.25[c]
Lightweight aggregate		↓	–

Parameter		**Carbonation coefficient**	
Name	**Range**	**Increase ↑ decrease ↓ similar →**	**By a factor**
Curing time	1 → 28 day	↓	1.1–2.5; Ratio depends on SCM, degree of hydration, curing type
Curing temperature	20 °C → 60 °C	↓	Ratio depends e.g. on type of SCM resp. on calcium carbonate polymorph formed
	60 °C → 80 °C	↑	
Constant RH at 20 °C	50–55% RH → 90%RH	↓	0.4 ± 0.4[b]
	50–55% RH → 10%RH	↓	0.0[b]
Temperature	20 °C → 40 °C	↑	1.13 ± 0.04[b] 1.17 ± 0.07[c]
CO_2-concentration when related to natural CO_2 by the square root relationship	> 1–100 vol%CO_2	↓	Dependent on type and replacement level of SCM
O_2-, N_2- and CO_2-diffusion, H_2O-permeability	Upon carbonation	↑[c] ↓[b]	Dependent on the moisture state
O_2-, CO_2- permeability	Upon carbonation	↑[b, c]	
Capillary suction	Upon carbonation	↓[b, c, e]	0.3–0.9

[a]Water/cement + SCM, [b]Plain PC, [c]Blended cementitious material containing pozzolan or slag, [d]Aggregate/cement, [e]Except increase at high BFS replacement level

2 Suitability of existing accelerated testing methodologies to evaluate carbonation

2.1 Overview of existing testing methodologies for evaluating carbonation of concrete

A critical analysis of the standardised testing methodologies that are currently applied to determine carbonation resistance of concrete in different regions showed [13] that there are at least 16 different standards or recommendations being actively used for this purpose (see Table 2), with significant differences in sample curing, pre-conditioning, carbonation exposure conditions, and methods used for determination of carbonation depth after exposure. This overview also addressed the current practice in regions where no standards exist for determining carbonation resistance and highlights how changes in testing procedures influence the carbonation depths recorded and the carbonation coefficient values calculated.

Considering the importance of accurately determining carbonation potential of concrete, not just for predicting their durability performance, but also for determining the amount of CO_2 that concrete can re-absorb during or after its service life, it is imperative to recognise the applicability and limitations of the results obtained from different tests. This will enable researchers and practitioners to adopt the most appropriate testing methodologies to evaluate carbonation resistance, depending on the purpose of the conclusions derived from such testing (e. g. materials selection, service life prediction, CO_2 capture potential).

Table 2. Summary of standardised testing methods applied to assess carbonation resistance of concrete. Reproduced from [13].

Geographical scope	Standard ID	Title
China	GB/T 50082-2009**	Standard for test methods of long-term performance and durability of ordinary concrete
Europe	EN 12390-10:2018	Testing hardened concrete. Determination of the carbonation resistance of concrete at atmospheric levels of carbon dioxide
Europe	EN 12390-12:2020	Testing hardened concrete. Determination of the carbonation resistance of concrete. Accelerated carbonation method.
Europe	EN 13295:2004	Products and systems for the protection and repair of concrete structures. Test methods. Determination of resistance to carbonation
Europe	EN 14630:2006 *	Products and systems for the protection and repair of concrete structures. Test methods. Determination of carbonation depth in hardened concrete by the phenolphthalein method
France	XP P18 458:2022	Tests for hardened concrete. Accelerated carbonation test - measurement of the thickness of carbonated concrete
Global	RILEM CPC-18 (1988)*	Measurement of hardened concrete carbonation depth
Global	ISO 1920-12:2015	Testing of concrete - Part 12: Determination of the carbonation resistance of concrete - Accelerated carbonation method
Italy	UNI 9944:1992 (withdrawn 2019)	Corrosion and protection of reinforcing steel in concrete. Determination of the carbonation depth and of the chlorides penetration profile in concrete
India	IS 516 (Part-2/Sec 4) 2021	Hardened Concrete — Methods of Test Part 2 Properties of Hardened Concrete other than Strength Section 4: Determination of the carbonation resistance by accelerated carbonation method
Norway	NT Build 357 :1989	Concrete, repairing materials and protective coating – carbonation resistance
Portugal	LNEC E391:1993	Concrete. Determination of accelerated carbonation
Spain	UNE 83993 – 1: 2013	Concrete durability. Testing method. Determining the carbonation penetration rate in hardened concrete. Part 1: Natural method
Spain	UNE 83993 – 2: 2013	Durability of concrete. Test method. Measurement of carbonation penetration rate in hardened concrete. Part 2: Accelerated method.
Switzerland	SIA 262/1: 2019	Concrete Structures: Supplementary Specifications
The Netherlands	CUR-Aanbeveling 48:2010	Procedures, criteria and test methods for testing the suitability of novel cements for application in concrete and for the equivalent performance of concrete with fillers
United Kingdom	BSI 1881-210:2013	Testing hardened concrete. Determination of the potential carbonation resistance of concrete. Accelerated carbonation method

* Standards that solely indicate how to determine carbonation using a pH indicator
** It must be noted that in 2024 a new version of this standard was published - GB/T 50082-2024 'Standard for test methods of long-term performance and durability of concrete'

2.2 Influence of testing parameters on the carbonation performance of concrete with SCMs

To understand how the measured carbonation rates can be influenced by adopting different standard prescriptions, an extensive interlaboratory test (ILT) with 22 participating laboratories was conducted to determine the carbonation depths and coefficients for mortar and concrete by following several (inter)national standards. Specimens were produced with three different cement types CEM I, CEM II/B-V, and CEM III/B, being the most widely used in concrete practice. The outcomes of this study [14] showed that the carbonation rate based on the carbonation depths after 91 days of accelerated testing can be considered as a good estimate of the potential resistance to carbonation (while carbonation rates determined based on shorter test durations are less reliable). For natural carbonation, an exposure period of at least one year was essential to reach a constant carbonation rate over time [15].

All the standardised testing protocols evaluated in this study ranked the three cement types in the same order of carbonation resistance (high to low) (see Table 3). Also, when comparing accelerated and natural carbonation methods, it could be concluded that ranking of cement types was similar. Unfortunately, large variations within and between laboratories did not allow to draw clear conclusions regarding the effect of sample pre-conditioning and carbonation exposure conditions on the carbonation performance of the specimens tested. The effect of these curing conditions was more pronounced for CEM I than for CEM III mixes. The variation between laboratories was even larger than the potential effect of raising the CO_2 concentration from 1 to 4 %. It was also found that 28 days water curing resulted in smaller carbonation depths compared to sealed curing, while the opposite was true when water curing was limited to 3 or 7 days.

Upon natural carbonation exposure [15], environmental parameters have an important effect on the carbonation rate, however, differences between the mean carbonation rates originating from indoor and sheltered outdoor natural exposure with different exposure conditions and curing regimes were insignificant for each considered cement type. For both natural and accelerated carbonation, the carbonation rate increased by 18% when the aggregate-to-cement ratio increased by 1.79 (concrete versus mortar). This correlation seems insensitive to binder type and exposure method. Finally, the best correlation between natural and accelerated carbonation was found when adopting the EN 12390-10 (specifically natural indoor exposure) and EN 12390-12 (accelerated exposure) methodologies, when results from more than one laboratory were considered.

Additional analyses were performed on selected samples from the ILT to determine the progress of carbonation with optical pH measurements, and results were reported in [16]. The phase composition was determined by X-ray diffraction, attenuated total reflectance Fourier transform infrared spectroscopy, and thermogravimetric analysis. Additionally, the CO_2 captured in three-year-old naturally carbonated samples was assessed and contrasted against the reactive CaO content. Results revealed that there was no direct relation between $CaCO_3$ content and pH after carbonation when considering different cement types. Carbonation degree varied more with cement type than with exposure conditions (indoors / sheltered outdoors) (Figure 1).

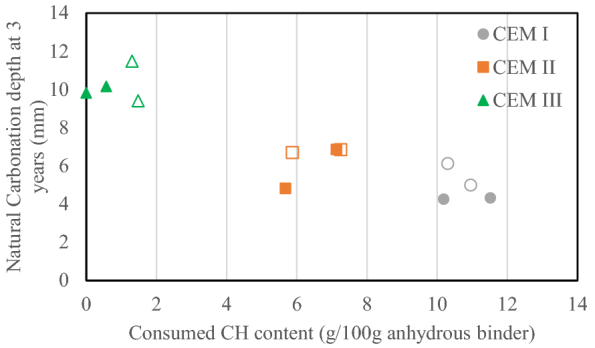

Figure 1. Consumed portlandite content versus the 3-years natural carbonation depth (mm). Full markers represent samples exposed to an indoor environment, and hollow markers represent samples exposed in a sheltered outdoor environment. Green markers for CEM III, orange for CEM II and grey for CEM I. Reproduced from [16].

A reduced clinker content led to lower pH values in carbonated and uncarbonated zones. Notably, samples containing CEM II displayed the largest formation of $CaCO_3$ which, divided by the theoretical maximum amount of $CaCO_3$ from reactive CaO, signified the highest degree of carbonation among the cement types studied.

Table 3. Overall summary of ranking and significance of differences in 91-days of accelerated carbonation depth of mortar and concrete after predefined curing for the ILT and standard curing for the considered cement types (significant = sign. and not significant = not sign). Reproduced from [14] where detailed information about the statistical analysis methodology adopted to determine the significance is provided.

Specimen type	**Accelerated carbonation method**		**Ranking of cement types with regard to the carbonation depth**	**Difference between cement types**		
				CEM I versus CEM II	**CEM I versus CEM III**	**CEM II versus CEM III**
Mortar	Predefined curing	1%	**CEM II < CEM I < CEM III**	**Not sign.***	Sign.*	Sign.*
		2%	CEM I < CEM II < CEM III	**Not sign.***	Sign.*	Sign.*
		3%	CEM I < CEM II < CEM III	Sign.*	Sign.*	**Not sign.***
		4%	CEM I < CEM II < CEM III	**Not sign.***	Sign.*	Sign.*
	EN 13295	1%	CEM I < CEM II < CEM III	Sign.	Sign.	Sign.
	Variant to EN 13295	1%	**CEM II < CEM I**	**Not sign.**	–	–
	fib	2%	CEM I < CEM II < CEM III	**Not sign.***	Sign.*	Sign.*
	EN 12390-12	3%	CEM I < CEM II < CEM III	Sign.*	Sign.*	**Not sign.***
	LNEC E391	4%	CEM I < CEM II < CEM III	Sign.	Sign.	Sign.
	SIA 262/1	4%	CEM I < CEM II < CEM III	**Not sign.***	Sign.*	Sign.*
	BSI 1881-210	4%	CEM I < CEM II	Sign.	–	–
	GB/T50082	20%	CEM I < CEM II < CEM III	Sign.	Sign.	Sign.
Concrete	Predefined curing	1%	CEM I < CEM II < CEM III	Sign.**	Sign.**	**Not sign.****
		2%	CEM I < CEM II < CEM III	**Not sign.**	Sign.	**Not sign.**
		3%	CEM I < CEM II < CEM III	Sign.	Sign.	Sign.
		4%	CEM I < CEM II < CEM III	Sign.*	Sign.*	Sign.*
	EN 13295	1%	CEM I < CEM II < CEM III	Sign.*	Sign.*	Sign.*
	Variant to EN 13295	1%	CEM I < CEM II	**Not sign.**	–	–
	fib	2%	**CEM II < CEM I < CEM III**	**Not sign.**	Sign.	Sign.
	EN 12390-12	3%	CEM I < CEM II < CEM III	Sign.	Sign.	Sign.
	LNEC E391	4%	CEM I < CEM II < CEM III	Sign.	Sign.	**Not sign.**
	SIA 262/1	4%	CEM I < CEM II < CEM III	**Not sign.***	Sign.*	Sign.*

*Variances not homogeneous
**Unequal sample sizes

2.3 Defining the connections between material mix design and carbonation performance

The work of TC 281-CCC also involved the creation and critical analysis of a comprehensive database, consisting of 1044 concrete and mortar mixes with their associated carbonation depth data over time, reported as a Supplementary File 1 in [17]. The dataset comprises mix designs with a large variety of binders with up to 94 % SCMs, collected from the previously described experiments conducted by the TC, the scientific literature and from unpublished testing reports contributed by TC participants. The database includes chemical composition and physical properties of the raw materials, mix-designs, compressive strengths, curing and carbonation testing conditions. Natural carbonation was recorded for

several years in many cases with both indoor and outdoor results. The database was analysed, and results were reported in [17]. This included investigating the effects of binder composition and mix design, curing and preconditioning, and relative humidity on the carbonation rate. Furthermore, the accuracy of accelerated carbonation testing as well as possible correlations between compressive strength and carbonation resistance were evaluated.

The assessment revealed that the $w/CaO_{reactive}$ ratio is a decisive factor for carbonation resistance, while curing and exposure conditions also influence carbonation. Under natural exposure conditions, the carbonation data exhibit significant variations (Figure 2). Nevertheless, probabilistic inference suggests that both accelerated and natural carbonation processes follow a square-root-of-time behaviour, though accelerated and natural carbonation rates cannot be converted into each other without applying correction factors. Additionally, a machine learning technique was employed to assess the influence of parameters governing the carbonation progress in concretes.

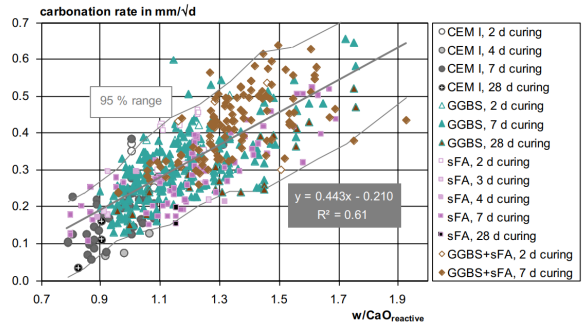

Figure 2. Carbonation rate vs. $w/CaO_{reactive}$ for natural carbonation at 20 °C and 60–65% RH for all binder types and curing times. The best fit line and 95% range apply for 7 d curing. Reproduced from [17].

This resulted in an equation to estimate the carbonation depth d_c (mm) based on the main influencing parameters:

$$d_c = a \cdot 10^{-b f_c} \cdot \left(1 - \frac{RH}{100}\right)^c \cdot [CO_2]_0{}^d \cdot t^e \cdot CaO_{reactive}{}^{-f} \cdot 10^{-977 \cdot g/T}$$

where a, b, c, d, e, f, and g are inferred parameters, f_c is the compressive strength (MPa), RH is the relative humidity during carbonation (%), $[CO_2]_0$ is the CO_2 concentration at the surface (%), t is the time (days), and T is the temperature (in Kelvin) during carbonation.

This analysis also revealed a lack of studies determining the influence of the RH during carbonation exposure on the carbonation degree. Considering the exposure RH influences the cement hydration evolution, and the saturation degree of the pore structure of concrete specimens, more studies are required to better understand the carbonation progress of cementitious materials exposed to different microclimates. This with the objective to develop more reliable and accurate equivalences between natural and accelerated carbonation results.

3 Influence of loading on carbonation performance of concrete with SCMs

An additional effort was made to study the effect of load in combination with carbonation. In real structures, concrete is subject to various loading conditions, which might influence the carbonation rate and therefore also the service life estimations for reinforced concrete structures. Five different laboratories conducted comparative testing of Portland cement concrete, with and without SCMs, under the combined action of carbonation and mechanical loading [18]. The results indicated that the carbonation depth of concrete undergoing mechanical loading is lower in the case of a limited compressive load, and higher in the case of a high compressive load or tensile load, compared with unloaded specimens.

The relative carbonation depths recorded were 9% to 16% lower than those recorded in non-loaded specimens, when the concrete was subjected to 30% failure load in compression, independent of CO_2 concentration and the presence of SCMs. Specimens subjected to higher loading (60% load level) reported on average a 13% increase in carbonation depth compared to non-loaded specimens (Figure 3).

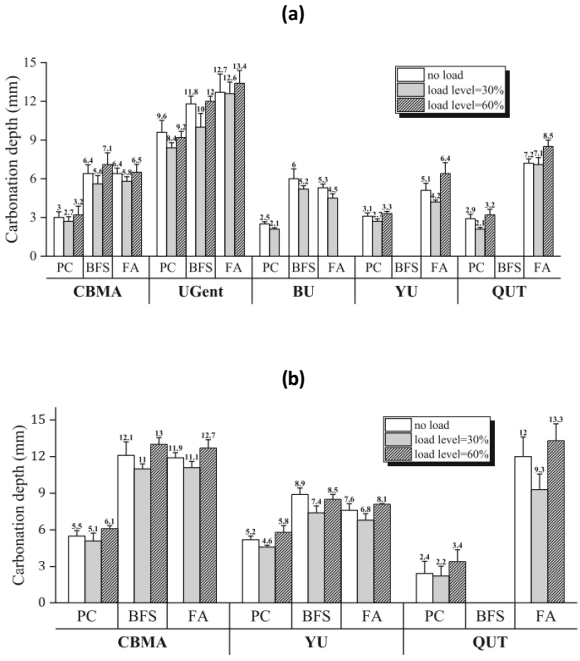

Figure 3. Carbonation depth measured in concrete specimens subjected to compressive loading while exposed to (a) 2% CO_2 and (b) 20% CO_2 for 28 days. PC – Concrete with Portland cement, BFS - Concrete with 50% Portland cement and 50% blast furnace slag, FA- Concrete with 70% Portland cement and 30% fly ash. The labels CBMA, UGent, BU, YU and QUT stand for the names of the organisations where results were collected. Reproduced from [18].

Conversely, subjecting the concrete to tension loading led to a gradual increase of carbonation and up to 70% higher carbonation depths were recorded when the material reached 60% of the tensile failure load, when compared with carbonation values recorded in non-loaded specimens. The clear and significant effect of mechanical loading on

carbonation of concrete, with or without SCMs, should not be neglected in the service life prediction of concrete structures. Depending on the potential application of the concrete, carbonation performance under loading conditions should be conducted. As there is no universal standard prescribing how the combined effect of loading and carbonation can be evaluated in structural concrete, the recommendation 'Test method to determine the effect of uniaxial compression load and uniaxial tension load on concrete carbonation depth' [19] was developed. This recommendation provides information regarding loading set-ups that can be adopted, a workflow for conducting the testing and data collection, and a guideline for calculating average carbonation depths of loaded specimens.

4 Does carbonation lead to corrosion of steel reinforcement?

Carbonation of concrete, and the associated pH reduction, is generally assumed to be the primary cause of reinforcing steel corrosion, and a critical review on this aspect was conducted by some of the TC members. This was motivated by the fact that this mindset has long dictated the research priorities surrounding the developments towards new, low-emission binders. However, by reviewing documented practical experience and scientific literature, members of the TC argue that this approach is rather simplistic, and a more holistic approach is required to understand the connection between carbonation and steel reinforcement corrosion [20]. In the review it is reported that there are many cases from engineering practice where carbonation of the cementitious matrix surrounding the steel did not lead to noticeable corrosion or to corrosion-related damage at the level of a structure.

The influencing factors that can, however, lead to considerable corrosion damage are identified as being the moisture state, the microstructure of the carbonated concrete, various species that may be present – even in minor amounts – in the concrete pore solution, and the cover depth (Figure 4). This demonstrates that a reduced pH alone is not sufficient to lead to significant steel corrosion in concrete. This observation has profound consequences for the established approach of assessing the durability performance based on carbonation testing and modelling, as other properties of the concrete cover layer (e.g. moisture movement) should be evaluated to infer corrosion potential of carbonated structures.

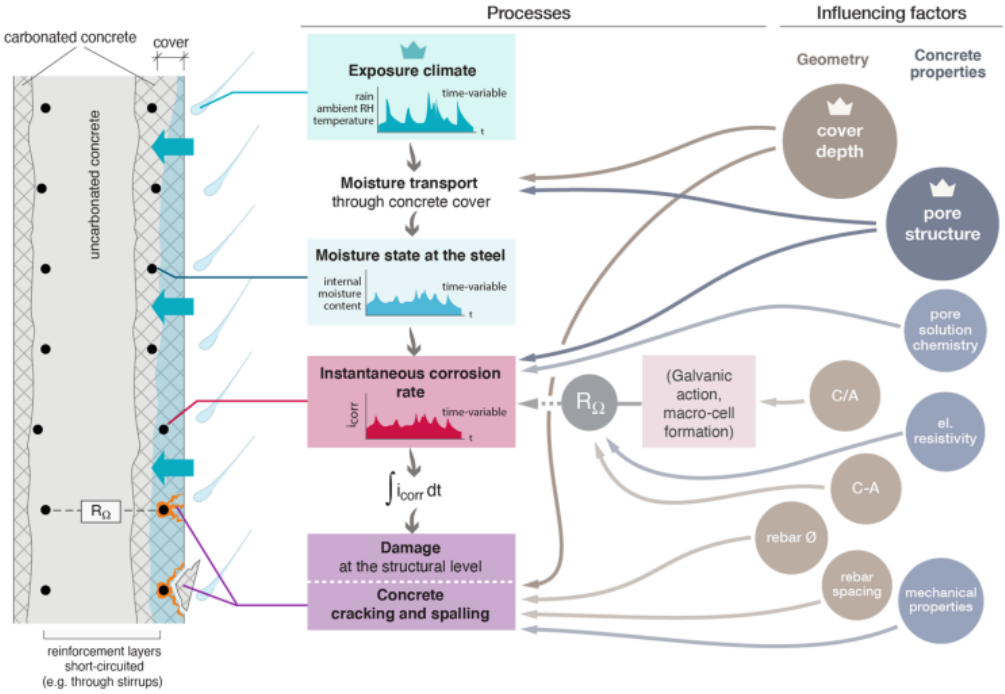

Figure 4. Summary of processes leading to corrosion-related damage in carbonated reinforced concrete (in the absence of chlorides) and their influencing factors. C/A = cathode / anode area ratio; C-A = cathode – anode distance; RΩ = ohmic concrete resistance in the galvanic element. The crown symbol highlights the most important influencing factors. Reproduced from [20].

5 Carbonation performance of alkali-activated mortars and concrete

A similar exercise of compiling and critically analysing carbonation data was performed specifically for alkali-activated concrete and mortar. For comparison purposes, data for blended Portland cement-based concretes with a high percentage of SCMs (≥ 66 % of the binder) were also included in this study [21]. The analysis indicated that *w*/CaO ratio and *w*/*b* ratio exert an influence on the carbonation resistance of alkali-activated concretes, but these parameters are not good indicators of the carbonation resistance when considered individually. A better indicator of the carbonation resistance of alkali-activated concretes under conditions approximating natural carbonation appears to be their *w*/(CaO + MgO_{eq} + Na_2O_{eq} + K_2O_{eq}) ratio, where the index 'eq' indicates an equivalent amount based on molar masses. Nevertheless, this ratio can serve as approximate indicator at

best, as other parameters also affect the carbonation resistance of alkali-activated concretes. In addition, the analysis of the database points to peculiarities of accelerated tests using elevated CO_2 concentrations for low-Ca alkali-activated concretes, indicating that even at the relatively modest concentration of 1 % CO_2, accelerated testing may lead to inaccurate predictions of the carbonation resistance under natural exposure conditions (Figure 5).

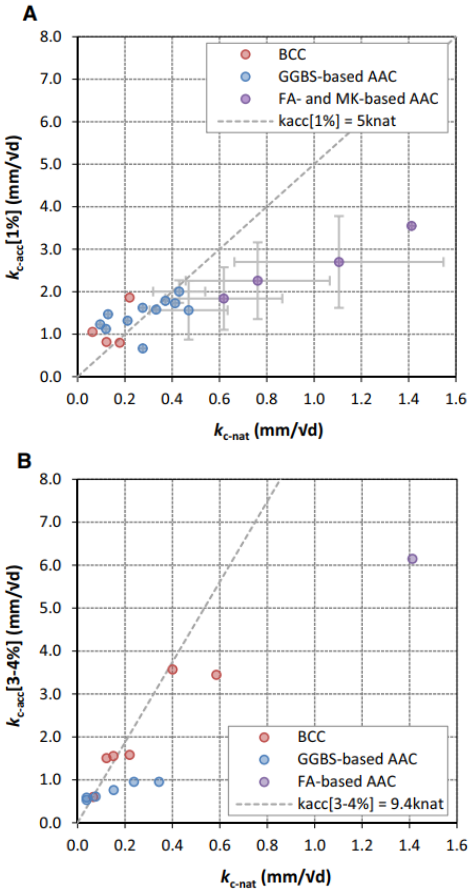

Figure 5. Carbonation coefficients obtained under accelerated conditions (A, $c_{CO2,acc}$ = 1%; B, $c_{CO2,acc}$ = 3–4%) versus carbonation coefficients obtained under conditions approximating natural carbonation (indoor/sheltered). Error bars represent the estimated s.d. of the results obtained in the round robin testing programme by RILEM TC 247-DTA. In the legend BCC, GGBS, FA and MK stand for blended Portland concrete, ground granulated blast furnace slag, fly ash and metakaolin, respectively. Reproduced from [21].

6 Engagement and dissemination activities

One of the main outcomes of the TC is the community that was created, as well as the collaborations that emerged over the years. Some photographs of the TC members are shared in Figure 6. During the life of the TC, 11 general meetings were held (in person and virtually), TC members delivered several talks in RILEM conferences and other events, as well as coordinated special sessions during the RILEM Spring Convention in Rovinj, Croatia, the RILEM annual week in Sheffield, UK (remotely), and during the SYNERCRETE conference in Milos, Greece.

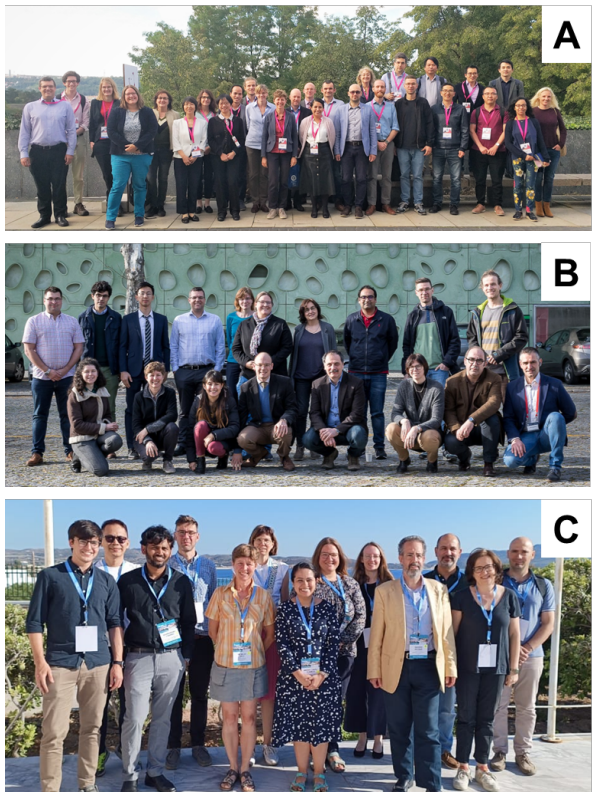

Figure 6. Photographs of attendees of RILEM TC 281-CCC to meetings in (A) Prague (2019), (B) Guimaraes (2020), and (c) Milos (2023).

7 Concluding remarks and research needs

The RILEM TC 281 CCC made significant contributions to advance the understanding of carbonation of concrete with SCMs and brought together researchers and practitioners with an interest in this durability phenomenon. Some concluding remarks and open questions that need to be addressed in future efforts include:

- For accelerated carbonation testing, it is important to promote the harmonisation of the sample pre-conditioning, and testing exposure conditions, particularly CO_2 concentration, in existing standards to enable comparisons of results from different studies to facilitate a better understanding of how the intrinsic properties of a specific concrete can be linked to its carbonation resistance.
- It remains unknown how best to translate carbonation rates obtained via accelerated tests to carbonation rates under natural conditions for different types of concrete. It is imperative to conduct experiments under natural carbonation exposure conditions, recording information about the microclimates the materials are being exposed to, in order to create a better understanding about realistic performance of concrete, which is not always captured via accelerated carbonation testing.
- Although carbonation testing guidelines are designed to simulate the worst-case scenarios when carbonation can take place, more studies evaluating the influence of varying relative humidities and temperatures when concretes are exposed to accelerated carbonation conditions are also needed to aid the creation of more

accurate correlations between natural and accelerated carbonation test results, to optimise material selection and concrete cover design for durability.

- Loading will have a significant impact in the carbonation progress. It was identified that under limited compression loading the carbonation depths were significantly lower than those obtained in unloaded samples. On the contrary, under tension loading the carbonation depths were significantly higher than those of unloaded specimens. This is independent of the accelerated carbonation exposure conditions (CO_2 concentration). This suggests that the concrete cover prescribed in standards for design of concrete for different exposure classes, could be revised considering the loading in service condition of the structural element to be produced.
- From practical experience there does not seem to be a direct correlation between reduction of pH associated with concrete carbonation, and corrosion of steel reinforcement. This is associated with the fact that many other factors will influence the initiation and propagation of corrosion processes in reinforced concrete. Therefore, in order to interrogate the durability performance of steel reinforced concrete structures it is imperative to evaluate corrosion of steel in carbonated concrete, particularly in novel cementitious systems with a limited service track record.
- Carbonation rates of alkali-activated blast furnace slag concretes, when determined by natural or accelerated carbonation testing, are comparable to those of blended Portland concrete with high volume of slag. This demonstrates that it is not true that all alkali-activated concrete will carbonate more and/or faster than blended Portland concretes. Also, accelerated carbonation testing, particularly at CO_2 concentrations higher than 1%, does not seem to provide reliable results regarding carbonation resistance of low-Ca alkali-activated materials, when compared with results obtained under natural carbonation exposure. Therefore, natural carbonation studies of alkali-activated concretes are recommended for service-life prediction.
- There are concerns about using pH indicating solutions for determining carbonation depths, and therefore CO_2 uptake by concrete, as there is not a direct correlation between pH changes captured by a pH indicator and the amount of carbonates that can be forming in cementitious materials, particularly when blended with SCMs. This and other open questions related to estimating the CO_2 uptake capacity of concrete, motivated the creation of the RILEM TC CUC - Carbon dioxide uptake by concrete during and after service life [21].

It is worth mentioning that the activities of the TC mainly centred on evaluating performance of both blended Portland and alkali-activated cementitious materials produced with conventional SCMs (e.g. mainly fly ash or blast furnace slag). However, there is great interest in adopting new SCMs from natural (e.g. natural pozzolans, clays) and secondary sources (e.g. biogenic ashes, metallurgical slags), but their carbonation resistance has not been extensively studied. Consequently, it is of critical importance to determine if the existing knowledge about how specific phase assemblages and pore structures relate to carbonation performance, is applicable to materials produced with non-conventional SCMs. Equally there is a need to evaluate the interactions of CO_2 with materials with different cement chemistries (e.g. calcium aluminate cements, magnesium-based cements) to determine their long-term durability potential. The experiences of this TC can serve as a foundation to conduct similar studies to resolve the many open questions about carbonation resistance of non-conventional cementitious materials.

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Authorship statement (CRediT)

Nele De Belie: Conceptualization, Writing – Original Draft, Writing – Review & Editing. **Susan A. Bernal:** Conceptualization, Writing – Original Draft, Writing – Review & Editing.

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