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Report of RILEM TC 281-CCC: effect of loading on the carbonation performance of concrete with supplementary cementitious materials — an interlaboratory comparison of different test methods and related observations

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Abstract Durability of concrete with supplementary cementitious materials (SCMs) is crucial to the longevity of our built environment. Current research on the carbonation performance of concrete focuses on determining changes in microstructure induced by the chemical and physical interactions of CO_2 with the cement phase in samples that do not undergo loading. Although this approach has enabled us to understand the chemical carbonation durability of concrete, the deterioration process is certainly not realistic considering the in-service conditions of structural concrete. Therefore, five different laboratories from RILEM TC 281-CCC WG4 conducted comparative testing of Portland cement concrete with/without SCMs under the combined action of carbonation and mechanical loading. The results indicated that the carbonation depth of concrete undergoing mechanical loading is lower in the case of a limited compressive load, and

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higher in the case of a high compressive load or tensile load, compared with unloaded specimens. The relative carbonation depth was decreased by 9–16% at 30% of the failure load in compression, independent of CO_2 concentration and the presence of SCMs, while it was increased up to 13% at a 60% load level at most. Tension made the carbonation depth gradually increase, and up to 70% higher carbonation depth was reached at 60% of the tensile failure load. The combined effect of carbonation in concrete with SCMs and mechanical loading should therefore not be neglected in the service life prediction of concrete structures.

Keywords Durability · Concrete carbonation · Supplementary cementitious materials · Compressive loading · Tensile loading · Combined actions

1 Introduction

As concrete with supplementary cementitious materials (SCMs) is widely used in modern construction, its durability performance has become critically important to ensure that these materials can withstand the in-service environmental conditions they are exposed to. However, evaluation of durability according to standardized test methods and specifications is often carried out on concrete specimens in a load-free condition and therefore does not consider the effect of the service load, despite the majority of structural concrete will experience different loading stresses. Evaluating the durability of concrete under loading is challenging as there is no standardized methodology that recommends how such experiments need to be performed and how representative the results obtained from them might be, compared with real-life observations.

When investigating the effect of load on concrete durability under different environmental conditions, whether carbonation, chloride ingress or other exposure types, similar loading frames for applying external mechanical load can be used. For applying different types of loads including uniaxial compressive load [1, 2], uniaxial tensile load [3, 4], 3-point bending load [5], and 4-point bending load [6, 7] by use of external bar tendons, several loading frames have been designed. Some researchers further added springs, especially disc springs (Belleville washer), on the bar tendons in these loading setups. In this case, the load is transmitted through the springs and not merely through the bar tendons. The applied load maintains constant by the buffering effect when inevitable stress loss happens, while keeping the total weight of the setups as light as possible. Moreover, the conventional creep setup can be effectively adopted for assessing

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the combined effect of carbonation and uniaxial compressive load under natural or controlled accelerated conditions if the environmental chamber used for inducing accelerated carbonation is large enough and can support enough weight. In this case, the load can be kept stable by the pressure exerted by the compressed air in a gas container. An extensive overview of dedicated experimental setups for investigating concrete under combined mechanical load and carbonation has been given in a recent review article, which provides an in-depth evaluation of their feasibility, reliability, advantages, and disadvantages related to the load level and loading conditions [8]. The same review furthermore analyses how stress damage induced by external mechanical load affects the carbonation resistance and how sustained loads influence the gas permeability and carbonation depth even without creating visible damage. The authors discuss how compressive load densifies concrete and slows down the carbonation slightly at a low load level. However, the carbonation rate significantly increases once a certain threshold is reached because of the generation and connection of cracks. In addition, tensile loads always result in a higher porosity of concrete and an increase in carbonation rate. It was pointed out in conclusion that more efforts should be made to determine the threshold mentioned above so that acceleration of carbonation can be avoided or considered in service life design.

In order to shed more light on the combined action of carbonation and load, specifically for concrete containing supplementary cementitious materials (SCMs), the RILEM Technical Committee TC 281-CCC on "Carbonation of concrete with supplementary cementitious materials" created the Working Group (WG4). The objectives of WG4 are to identify potential testing setups to enable the evaluation of the combined actions of loading and carbonation, and subsequently quantify the impact of such stresses on the carbonation rate. To achieve this goal, a comparative testing programme was performed in five different laboratories, collecting information regarding the testing method and the results obtained. This activity enabled to create a deeper understanding of the potential combined effect of loading conditions and carbonation of concrete.

2 Preparation of specimens

The laboratories that participated in the interlaboratory test and provided results are listed in Table 1, among which all five labs participated the carbonation test under compression and only CBMA conducted the test under tension.

2.1 Raw materials

Portland cement (PC) with a strength class of 42.5 N was used in the comparative tests. The cement composition in different laboratories is slightly different due to using different standard specifications. P I cement that conforms to Chinese National Standard GB 175 [9] contains only cement clinker and gypsum and was used in CBMA, QUT, and YU. CEM I which conforms to European standard EN 197-1 [10] used in the Magnel-Vandepitte laboratory contains 3.98 wt% limestone and 1 wt% silica powder. Portland cement with a 43 grade which conforms to Indian Standard IS 8112:1989 [11] was used in BU. Ground granulated blast furnace slag (BFS) and fly ash (FA) were used as SCMs. The related basic properties of cement and SCMs are listed in Tables S1 to S4 in Supplementary Information 1.

The fine aggregate used in all labs was river sand with a density range of 2620 – 2680 kg/m^3, a sediment percentage less than 0.7% and a fineness modulus of 2.8. The coarse aggregate used in BU and YU was granite stone with a density of 2656 and 2550 kg/m^3, respectively, and that in other labs was limestone with a density of around 2720 kg/m^3. The tested sediment percentage was less than 0.3%, and water absorption was around 0.1 – 0.6% in different labs. The grain size distributions of fine and coarse aggregate used in CBMA, UGent and BU are shown in Figure S1.

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Table 1 Laboratories participated in the interlaboratory test

No.	Laboratories	Abbreviations
1	China Building Materials Academy, Beijing, China	CBMA
2	Magnel-Vandepitte Laboratory for Structural Engineering and Building Materials, Ghent University, Ghent, Belgium	UGent
3	Bennett University, Uttar Pradesh, India	BU
4	Qingdao University of Technology, Qingdao, China	QUT
5	Yantai University, Yantai, China	YU

2.2 Mix proportion

The prescribed mix proportions are given in Table 2. A slump of 110 mm was targeted by adjusting dosages of chemical admixtures.

Table 3 shows the slump and the chemical admixture dosage actually used in each lab, in which QUT used a naphthalene-based water reducer and CBMA, BU and YU used a polycarboxylate-based superplasticizer. At UGent, more than the required consistency was reached without any superplasticizer addition.

2.3 Specimen production

For carbonation tests under uniaxial load, the specimen size was selected based on the recommendation of RILEM TC 246-TDC, which proposed test methods to determine the influence of applied stress on chloride diffusion [3], but the length was reduced to 300 mm considering the dimensions of the carbonation chambers. Concrete prisms with a size of 100 × 100 × 300 mm were prepared for compression tests. Dumbbell-shaped concrete specimens with a cross-section of 70 × 70 mm and a length of 300 mm were prepared for tension tests (see Figure S2).

2.4 Curing procedure

All laboratories followed the following curing protocol for the carbonation test:

Step 1—After casting, the fresh concrete was covered with a plastic sheet and cured at 20 ± 2 °C until demolding at 1 d of age.

Step 2—After demolding, the specimens were immediately put into a saturated $Ca(OH)_2$ solution at 20 ± 2 °C and cured for 6 days.

Step 3—After curing in saturated $Ca(OH)_2$ solution, the specimens were preconditioned prior to carbonation exposure in a climate room at 65 ± 5% relative humidity (RH) and 20 ± 2 °C for 84 days.

It is worth noting that for the preconditioning in step 3, UGent controlled the climate room at 60 ± 5% RH, and YU at 95 ± 5% RH, due to the limitations posed by the curing conditions prescribed for other specimens that were present in the same room during this period, while other participants adhered to the prescribed preconditioning procedure. According to the test results, the carbonation depth of PC, FA, and BFS concrete within the curing and preconditioning period was less than 0.2 mm in CBMA, while significantly higher at UGent (2.4, 3.9, and 4.2 mm). A possible reason is the difference between raw materials, which apparently also leads to a difference in concrete consistency as discussed in Sect. 2.2.

In this interlaboratory comparison, it was chosen to subject the concrete samples to the combined action of mechanical loading and accelerated carbonation at the age of 90 days. It is well known that the pozzolanic or latent hydraulic reaction of SCMs, which improves the concrete microstructure, usually takes several months to have its main effect. A shortened curing time might cause an incompletely developed microstructure and an increased diffusivity. For the concrete types under study here, a comparison between the carbonation depth of concrete cured for 28 and 90 days and then (without loading) exposed to a CO_2 concentration of 2% or 20% at a temperature of 20 ± 2 °C and a RH of 65 ± 5% for 28 days is shown in Fig. 1. In addition, Fig. 2 shows the influence of curing time on PC concrete, loaded at 0, 30 or 60% of the failure load and exposed to a CO_2 concentration of 2 or 20% at a temperature of 20 ± 2 °C and a RH of 65 ± 5% for 28 days.

Table 2 Designed mix proportions of concrete

Concrete type	Cement I 42.5 (kg m^{-3})	Fly ash (kg m^{-3})	Blast furnace slag (kg m^{-3})	Sand (kg m^{-3})	Gravel (kg m^{-3})	Water (kg m^{-3})	w/c
PC	330	0	0	719	1162	198	0.6
FA	231	99	0				
BFS	165	0	165				

Table 3 Chemical admixture dosage and concrete slump in the five laboratories

Concrete type	Chemical admixture (kg m^{-3})					Slump (mm)		
	CBMA	UGent	BU	YU	QUT	UGent	QUT	Others
PC	0.7	0	0.33	0.5	0.74	210	100	110
FA	0.3		0.50	0.5	0	215		
BFS	0.5		0.75	0.5	–	225		

Figure 2 indicates that reducing the curing period from 90 to 28 days will increase the carbonation depth by 5 – 10%, 32 – 34%, and 24 – 33% for PC, BFS, and FA concretes in the range of 2 – 20% CO_2, respectively. It is clear that the difference in curing time has a major effect on the carbonation depth for BFS and FA concrete, while the effect is negligible for PC concrete. The BFS and FA have latent hydraulic and pozzolanic properties leading to the formation of secondary hydration products, especially in the period from a week up to 3 months after concrete mixing. The effect of longer curing is even more evident at a higher CO_2 concentration (20%), where a further increment in carbonation depth is noticed for PC, BFS, and FA concretes.

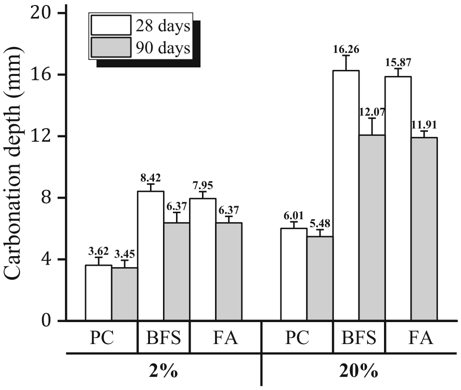


Fig. 1 Carbonation depth of concrete without load exposed during 28 days to 2% or 20% CO_2 after different curing times (results of CBMA)

3 Combination of carbonation and loading

In this study, the carbonation behaviour of loaded concrete was investigated under two CO_2 concentrations (2 and 20%) and two loading conditions (uniaxial compression and tension). The cured specimens were first loaded in the loading setups and then placed in a carbonation chamber for 28 days at the RH of 65 ± 5% and temperature of 20 ± 2 °C. Two stress ratios, 30 and 60%, were chosen to investigate the carbonation behaviour because the design concrete strength is normally somewhat higher than 60% of the characteristic strength under persistent and transient situations as mentioned by Eurocode 2 [12]. In the meantime, a compressive stress ratio of 30% still

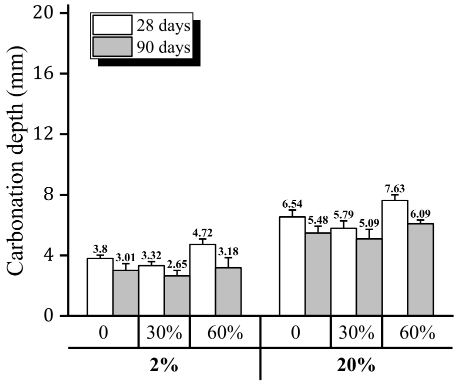


Fig. 2 Carbonation depth of loaded PC concrete exposed during 28 days to 2% or 20% CO_2 after different curing times (results of CBMA)

locates within the range of densification effect domination on the carbonation behaviour [13].

3.1 Loading setups

The setups and carbonation chambers to maintain a stable load and carbonation environment used in all participating labs are mainly of two types as shown in Figure S3, i.e., automatic compensation by hydraulic system (UGent and BU) and manual compensation by bolt & spring system (CBMA, QUT and YU). The schematic diagrams and principals of these two loading types are also shown in Figures S3a and b, respectively. When comparing the advantages and disadvantages of these two types for providing an uniaxial load, it can be concluded that the use of an hydraulic system or creep frame is certainly ideal, because a stable applied load is automatically maintained and it is much easier to install/uninstall specimens. The requirement for a large-enough CO_2 chamber is obviously one of its weaknesses. Manual load compensation by bolt & spring system, on the contrary, is much more flexible for many labs with a "small" carbonation chamber, because the disc springs can support large loads with a small installation space. The biggest issue is the inaccuracy of the initial load application and stress relaxation during the carbonation test. The stable load relies on a proper load-application method and regular load compensation, thus a real-time load monitoring is recommended. In general, both systems can provide stable load application under proper operation. Considering all the pros and cons of the two different loading setups, the participating labs could choose the suitable type depending on the available infrastructure, as long as this allowed to maintain a stable sustained load throughout the carbonation exposure period.

Without compensation, the applied load on the concrete specimen would gradually decrease due to drying shrinkage and creep. Therefore, all labs made regular adjustments to maintain the applied load in an acceptable range ($>$ 90% of the designed load in this study), except for the cases where the loading cell had auto-load compensation like at UGent. Load adjustment is recommended at least at ages of 5, 9, and 15 d for load levels of 30, 45, and 60% based on the test results in CBMA and BU, as shown in Figure S4.

3.2 Carbonation of the loaded specimens

Before the carbonation testing under uniaxial loads, the prism specimens were dried with a tissue to remove any remaining lime solution on the surface after the preconditioning process. Next, two opposite side surfaces (troweled surface and bottom surface during casting) and the two end surfaces were sealed with self-adhesive aluminium foil, leaving only the other two opposite side surfaces to be carbonated. In this way, two-dimensional carbonation in the corners and any effects of the casting direction, as discussed below, could be avoided. Then, the specimens were installed in the loading rig and loaded to the designed load level.

UGent further experimentally quantified the effect of the casting direction on the results for the trowelled surface and cast side and bottom surfaces, as shown in Figure S5. The tested specimens were cured for 21 days in step 3, which was different from the main curing procedure in Sect. 2.4. The results of 2% CO_2 carbonation tests with and without 45% load levels are shown in Fig. 3. It indicated that the carbonation at the bottom surface was only 1/3 of that of the top troweled surface and the side surfaces. The compressive load effect was, in absolute terms, similar for different surfaces. The main reason for the differences in carbonation depth between surfaces, is the slightly uneven distribution of aggregates in concrete caused by gravity during the specimen's casting. This will be more pronounced at the chosen, reasonably high w/c ratio. As a result, the volume content of aggregates is higher at the bottom than at the top. Considering the "dilution effect" and "tortuosity effect" of aggregate, the transport at different surfaces is certainly affected.

The 28-day failure loads were measured by a uniaxial loading test with a universal testing machine. The test procedure in CBMA, QUT and YU conformed with GB 50010-2010 [14] and that in UGent and BU conformed with EN 12390-3 [15] and IS 516:1959 [16], respectively. The compressive loading rate was slightly different in the five labs due to standard regulations. In CBMA, QUT and YU, it was 0.5 $\sim$ 0.8 MPa/s, and in UGent and BU, it was 0.6 MPa/s and 400 kg/min. The tensile loading rate in CBMA was in a range of 0.08 $\sim$ 0.10 MPa/s. The load values corresponding to a certain load level can then be determined.

It should also be noted that the specimens loaded in the rigs were recommended to be vertically placed in the carbonation chamber. According to the comparative test in QUT (Figure S6), horizontal positioning could lead to a 38 – 44% difference in carbonation depth, or even an entire change in the experimental load effect on the carbonation depth. A possible reason is that the specimen, bolts, springs and steel frame are more likely to slip, get stuck or jam when loading rigs are horizontally placed since such a setup is not intended for horizontal placement. Therefore, it would result in changes in stress distribution, despite the fact that the weight of the specimen is relatively small compared with the applied load. YU also compared the difference between two types of placements on three BFS concrete specimens under 60% load and 20% CO_2. The very limited results showed that the carbonation results were 7% greater when specimens were placed horizontally than when placed vertically.

3.3 Measurement of carbonation depth

After the carbonation test, the carbonated specimens were removed from the loading frame and then the carbonation depth was determined. The measured surface is the cross-section in the middle part of the prism sample, which can easily be obtained by splitting with the help of a universal testing machine. In the middle section, the uniaxial load is distributed more evenly compared to the end part, contributing to a more accurate determination of the influence of the uniaxial load on carbonation.

The measurement procedure was carried out using a solution of 1 g phenolphthalein in 70/30 vol.% ethanol/water as a colour indicator, sprayed with a fine mist on the freshly split surfaces of the prism specimen after a certain time interval. The formation of flow channels should be avoided according to ISO 1920-12 [17]. The zone that remains colourless is regarded as fully carbonated, and the colour change boundary is considered to be the carbonation front. The distance between the carbonation front and the exposed side was measured at least 5 points with the same interval at each exposed side surface. A picture of the carbonation depth measurement in UGent is shown in Figure S7. If the preset measuring point coincided with the surface of an aggregate, the actual position for carbonation measurement was taken in the mortar matrix close to the aggregate (but not exactly at the aggregate surface to avoid the influence of ITZ carbonation). In case a measuring point was located in a dense aggregate, the colour change boundary was imaginatively extended through the aggregate, connecting the limits on each side of the grain [10]. The average depth of all these measured points in one specimen was taken as the carbonation depth of the specimen. The average carbonation depth of at least three replicate specimens was regarded as the carbonation depth for one test group, with an accuracy of 0.1 mm.

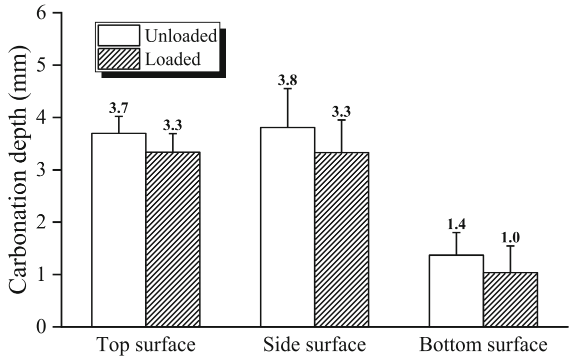


Fig. 3 Carbonation depths measured at different surfaces by UGent

The recommended time interval between spraying the indicator and splitting the prismatic specimen is distinctly different based on different national codes, such as 30 s in the Chinese Standard GB/T 50082-2009 [18] and 1 h in EN 12390-10: 2018 [19], respectively. Thus, CBMA conducted the comparison test on PC concrete following these two standards under 20% CO_2. The result at 28 days shows a mean value of 5.14 mm (1 h) and 5.33 mm (30 s) with a standard deviation of 0.21 and 0.12, respectively, which indicates no significant influence from the time interval. Therefore, the time of spraying the indicator was not imposed in subsequent tests.

4 Results and analysis

4.1 Mechanical strength

The 28 days compressive and tensile strengths of the cured concrete specimens were determined using the universal testing machine together with the loading rigs. The test results of cube and prism specimens are shown in Figs. 4, 5, and 6.

The differences in strength of the PC and SCM concrete are negligible in CBMA for both the compressive strength and the tensile strength, while the compressive strength of FA concrete is lower than PC concrete in other labs. There is also a slightly lower strength development identified in BU's results when using BFS containing concretes. The difference in strength development may be induced by the properties of the raw SCM materials. In addition, the strength of the YU specimens is higher than in most other laboratories. This can be explained by the higher RH (95 ± 5%) used during the preconditioning procedure, which leads to a higher cement and SCM hydration degree and a denser concrete sample.

4.2 Carbonation depth under compressive load

The carbonation test under compressive load was conducted in all five labs, and the experimental results of carbonation depth under compression are shown in Figs. 7 and 8, and also listed in Supplementary Information 2. All the data are obtained from the vertically placed specimens, except for YU who conducted all the tests with horizontally placed specimens.

The average carbonation depth without load is taken as the reference depth in each lab, and the relative carbonation depth of all the test data can be therefore determined by the ratio to the reference depth. The results of all data points for different CO_2 concentrations are presented in Figs. 9 and 10, respectively, as well as the fitting curves for each lab. The YU results are also derived from horizontally placed specimens. In this case, all the curves have the same starting point of the relative carbonation depth equal to 1, corresponding to the 0 load level. In Fig. 7, relatively large differences are noticed between different laboratories regarding the carbonation depths for the same concrete compositions and exposure conditions. This can mainly be attributed to the differences in raw materials used in the different labs (see Sect. 2.1), which resulted also in differences in the needed dosage of admixture and/or realized slump, as seen in Table 3. Nevertheless, in spite of the absolute differences in carbonation depths, all laboratories obtained a similar trend regarding the effect of load on the relative carbonation depth, as shown in Figs. 9 and 10.

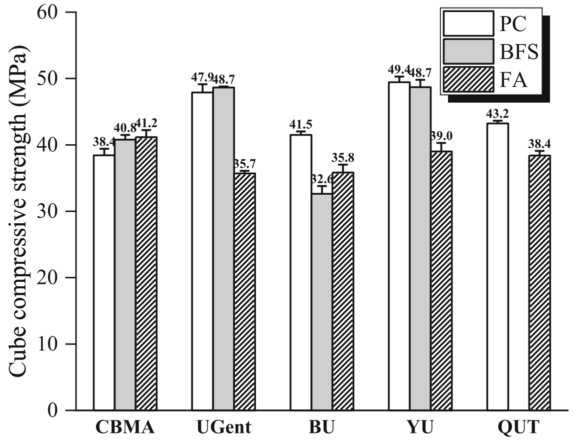


Fig. 4 Comparison of cube compressive strength at 28 days in five labs

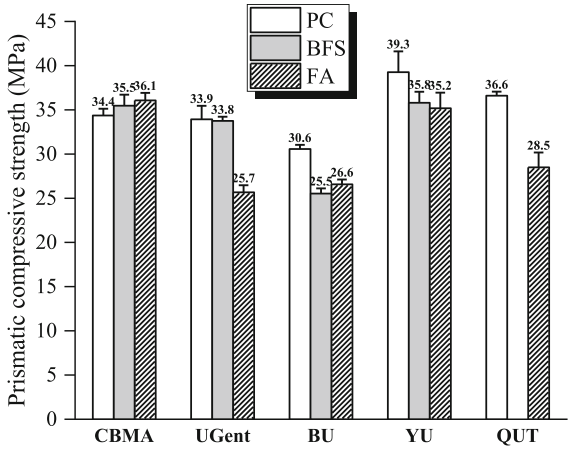


Fig. 5 Comparison of prismatic compressive strength at 28 days in five labs

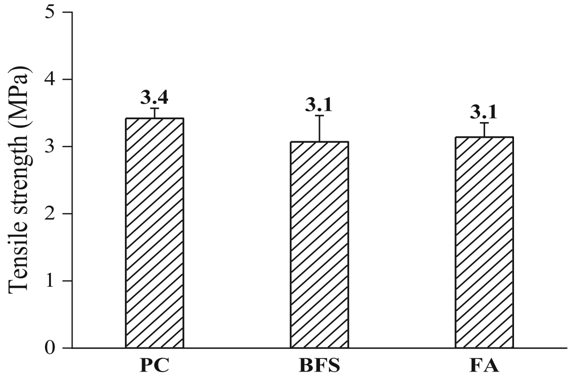


Fig. 6 Tensile strength at 28 days in CBMA

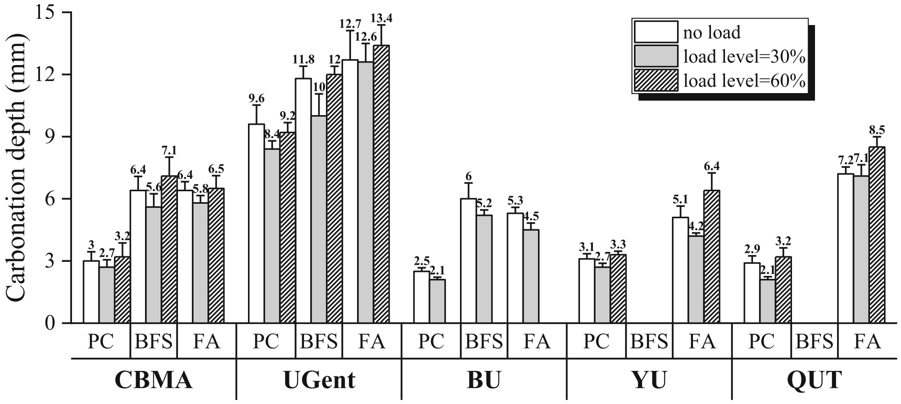


Fig. 7 Carbonation depth under compression at 2% CO_2

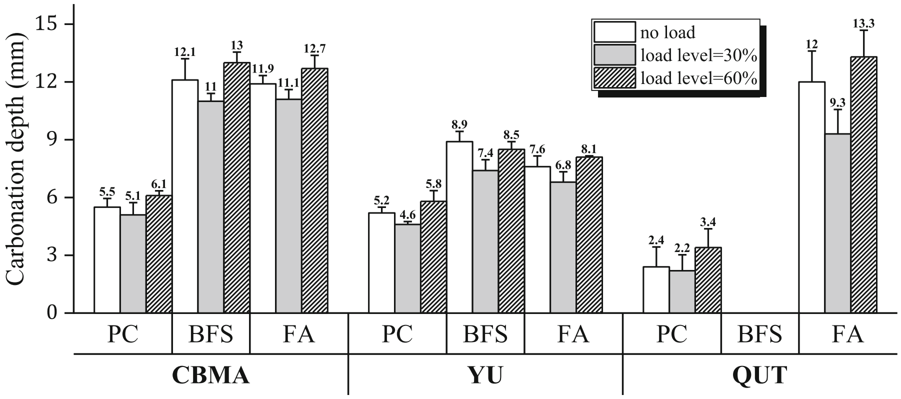


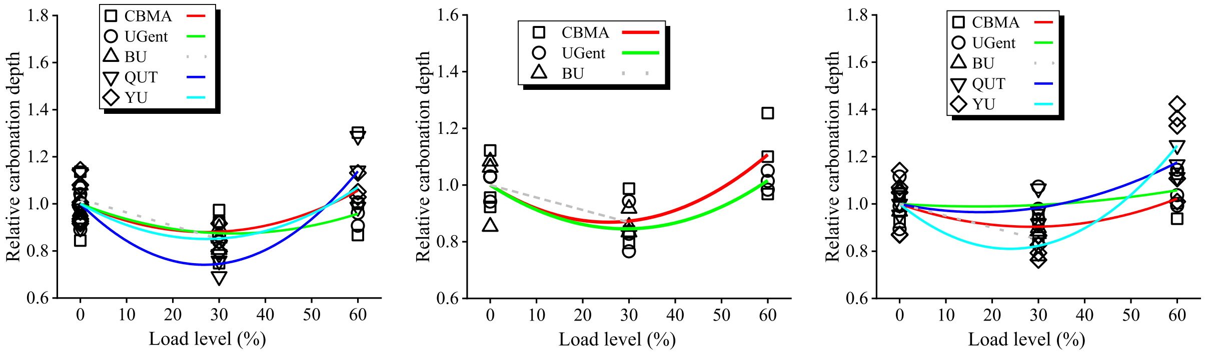
Fig. 8 Carbonation depth under compression at 20% CO_2

The carbonation depth under compressive load shows a decrease between the 0 and 30% stress ratios, while an increase is observed for the stress ratio of 60%. Such a phenomenon can be explained by the effect of the load on the diffusion paths available for CO_2 ingress. Since concrete will inevitably show defects like pores and cracks due to different types of shrinkage, those defects create diffusion paths for gases like CO_2. When the external compressive load is relatively low, these paths would narrow down or even close, reducing the carbonation rate to some extent. However, when the external load is increased, the microstructure would get damaged and microcracks will be formed, leading to an increase in carbonation rate [20, 21]. The two phenomena may exist simultaneously for intermediate loads, and successively dominate the resulting load effect [22]. The relative carbonation depth at the 30% stress ratio is around 0.84 – 0.91 times the value without load, where the relative carbonation depth of PC at 2% CO_2 is the lowest, and that of FA at 2% CO_2 is the highest (although the difference is insignificant when considering the large variability on the results). The relative carbonation depth at a load level of 60% is around 1.03 – 1.13 times the value without load. Therefore, the compressive load similarly affects the relative carbonation depth and shows similar profiles for different concrete mix compositions. Given the variability in the results, the effect of load on the carbonation depth is similar for CO_2 concentrations of 2 and 20% in general.

4.3 Carbonation depth under tensile load

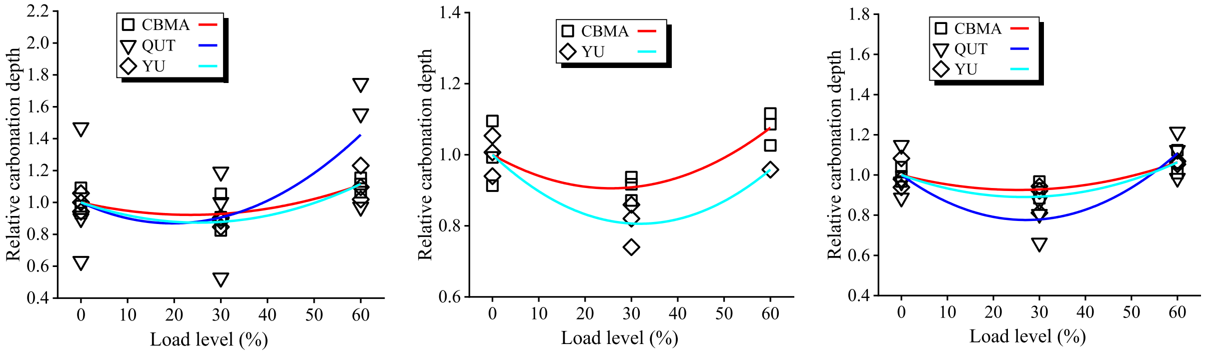
The carbonation test under tensile load has only been conducted by CBMA, and the corresponding detailed results are shown in Supplementary Information 2. The diagrams for carbonation depth and relative carbonation degree are demonstrated in Figs. 11 and 12, respectively.

It can be seen that the relative carbonation depth increased gradually from 1 to 1.4 – 1.7 with the increase of tensile load level. The load level of 60% increased the relative carbonation depth from 1 to



(a) PC (b) BFS (c) FA

Fig. 9 Relative carbonation depth for concrete at 2% CO_2



(a) PC (b) BFS (c) FA

Fig. 10 Relative carbonation depth for concrete at 20% CO_2

around 1.6 for all mixes at 2% CO_2. Unlike compression, tension causes pores' expansion and cracks' opening, which continuously promotes the CO_2 penetration into concrete specimens. As the tensile load level goes up, the microcracks may converge and form wider pathways for gases, leading to a much greater carbonation rate. This is the reason for the quadratic tendency in Fig. 12. At 20% CO_2, the load effect for PC concrete was identical to that at 2% CO_2. But the tensile load effect at 20% CO_2 moderated in the order of PC, BFS, and FA concretes. The quadratic tendency became almost linear.

5 Conclusions

The main task of RILEM TC 281-CCC WG4 was to determine the potential effect of loading on the carbonation performance of SCMs and develop suitable test methods and relevant test rigs to investigate the effect of load on the carbonation process in

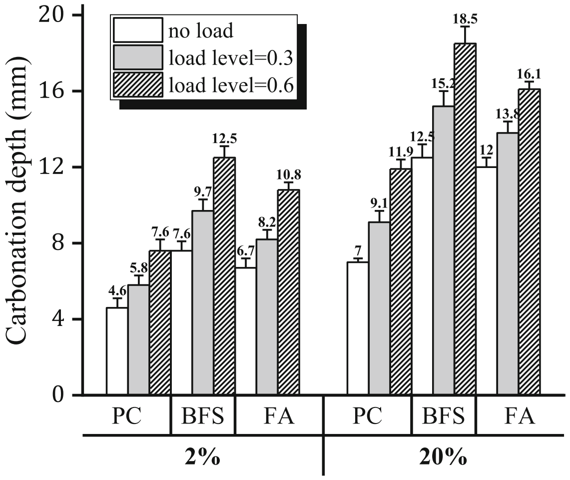
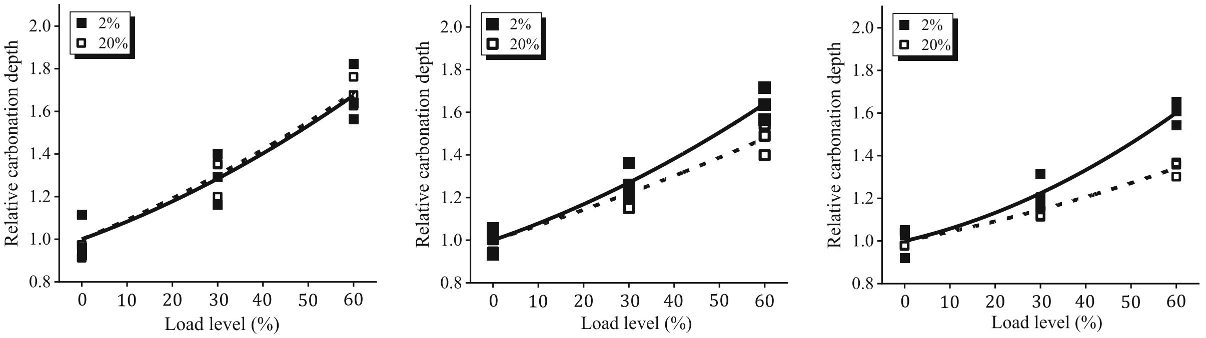


Fig. 11 Carbonation depth under tension at CO_2 concentrations of 2 and 20% as determined by CBMA



(a) PC (b) BFS (c) FA

Fig. 12 Relative carbonation depth under tension at CO_2 concentrations of 2 and 20% (CBMA results)

concrete. This paper's experimental results and analysis indicate that knowledge of the mechanical loading situation is critical to predicting carbonation depth in a realistic scenario. Furthermore, the influence of several key aspects of the test method on the carbonation depth was studied. Finally, based on all the results, the following conclusions are obtained.

1. The carbonation depth under compressive load shows an evident decrease at a stress ratio of 30% of the failure load, while it increases again at a stress ratio of 60%. The decrease at moderate load levels can be up to 16%.
2. Tensile load continuously increases the carbonation depth with a factor of 1.4 – 1.7 as the load level increases to 60% of the failure load. The rate of change also gradually increases, leading to a quadratic form for the relationship between the relative carbonation depth and the tensile load level.
3. The relationship between the carbonation depths of PC, BFS, and FA concretes is different in different labs, mainly owing to the difference in raw materials used in each participating lab. Nevertheless, the load effect remains similar and seems immune to such differences. The work in TC 281-CCC WG1 & WG2 [23, 24] provides a reference to explain the influence of SCMs on concrete carbonation behaviour.
4. The CO_2 concentration also slightly impacts the load effect for SCM concrete, especially under tension. In contrast with the PC concrete for which the tensile load effect is almost identical under CO_2 concentrations of 2 and 20%, the tensile load effect for BFS and FA concrete is more significant under 2% CO_2 concentration.

Based on the results from five participating labs, the test operations for concrete carbonation under mechanical loads have been gradually developed in this interlaboratory test. The final test method which aims to reduce measurement errors and result fluctuations will be compiled as a recommendation of RILEM TC 281-CCC. Regarding the perspective for further research, in addition to uniaxial tension and compression, the work of WG4 includes additional types of loading such as flexural loading, and research in this regard is currently being carried out at INSA-RENNES in France. We hope to extend the research in the future to various forms of loading associated with carbonation, such as impact loading and fatigue loading. It is also possible to predict the concrete carbonation depth under the combined action of load and CO_2 by model simulations. First modelling results have been published for Portland cement concrete [22], and the aim is to extend its application to concrete with supplementary cementitious materials by adjusting the variables in the modified carbonation model, such as the standard diffusivity of CO_2 in concrete and the standard reaction rate.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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