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RILEM TC 281-CCC - CARBONATION OF CONCRETE WITH SUPPLEMENTARY CEMENTITIOUS MATERIALS

Recommendation of RILEM TC 281-CCC: Test method to determine the effect of uniaxial compression load and uniaxial tension load on concrete carbonation depth

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Abstract The combination of environmental actions and mechanical load, which most structural concretes are subjected to, has a synergetic effect on the durability of concrete. The comparative test conducted by RILEM TC 281-CCC WG4 demonstrated and quantified the effect of an applied mechanical load on carbonation performance of concrete with supplementary cementitious materials. Although the effect of loading on the chemical durability of concrete should be taken into consideration for the development of realistic service life predictions, they have been widely overlooked so far. This recommendation proposed by RILEM TC 281-CCC WG4 proposes a testing method for determining the effect of applied load on the carbonation rate of concrete. It specifies a detailed experimental procedure to determine the carbonation development of concretes subjected to compressive and tensile loads. Therefore this recommendation will support the consideration of such combined effects in design codes.

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Keywords Concrete carbonation · Compressive load · Tensile load · Combined actions

1 Background

The majority of standardized testing methods for determining the durability of reinforced concrete structures, only evaluate the chemical durability of these materials by subjecting concretes to chemical deteriorating processes such as exposure to CO_2 (leading to a chemical reaction referred to as carbonation) or chlorides (simulating marine environments). Experimental results and observations in practice showed that this approach for evaluating durability is not a realistic, as the majority of structural concrete will be subjected to loading, and certainly not a conservative approach. The combination of mechanical loads and environmental actions may turn out to be more severe than any single action applied separately.

There are obvious synergetic effects between loads and environmental actions, which have been widely neglected so far, when developing testing methodologies for service life prediction of concrete. Considering that both loading and environmental stresses will be present during service life of concrete, the RILEM Technical Committee (RILEM TC) 246-TDC [1] was set up in 2011 to develop test methods to evaluate the durability of concrete under combined mechanical load and chloride penetration. Based on the comparative tests that was ran in five laboratories for six years, TC 246-TDC published a recommendation [1] and a final report [2] in 2017 on determining the service life of concrete under the combined action of chloride ingress and applied load.

After that, working group four (WG4) within RILEM TC 281-CCC was set up in 2018 to continue the work on evaluating the combined effect of mechanical load and carbonation on concrete performance. One major aim of WG4 was to develop a guideline for testing that allows the determination of the combined effect of mechanical load and carbonation, so results from future studies can be compared and a body of literature can be created to truly understand the phenomena taking place when concrete subjected to loading is carbonating. The proposed test methodology was critically validated by comparative tests run by members of WG4. Six laboratories in four countries participated in these comparative tests.

To establish a solid basis for the following experimental studies, an annotated bibliography containing publications on the durability of reinforced concrete structures under combined mechanical load and carbonation was compiled first [3]. It was proven that the load type and load level will influence the development of carbonation depth [4–11]. Based on the annotated bibliography and the specific experience of TC members, well-defined comparative tests have

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been carried out and evaluated. From the wide range of possible combinations in practice, the combination of uniaxial compressive or tensile load and carbonation at CO_2 concentrations of 2% and 20% were chosen in the tests. This for considering the variation in CO_2 concentrations recommended in different standardized testing methods currently adopted when evaluating performance in unloaded concrete [12]. The comparative test conducted for two rounds investigated the carbonation behaviour of concrete with or without supplementary cementitious materials (SCMs) under load [13]. The results of the interlaboratory investigation clearly indicate that the carbonation rate continuously increases under tension while it first decreases and then increases under compression, which forms the basis of the current recommendation.

Within the comparative test, the test method for concrete carbonation under mechanical loading has been gradually developed. By means of the specified test operations, fluctuations in the applied load are reduced, the concentration of carbon dioxide is controlled and the error in the carbonation depth measurement is reduced. Considering the fact that currently different setups and loading and carbonation conditions are adopted by different researchers, it is difficult to draw general conclusions. The need for a standardized testing procedure for evaluating the combined effect of loading and accelerated carbonation of concretes was identified, which is addressed in the present document. At the same time, TC 281-CCC WG4 members prepared literature compilations [3], reviews [4], research papers [5–7], theoretical analyses [8], and numerical simulations [9, 10] to investigate issues such as the effect of material composition, service life prediction, and theoretical modelling [11], which can be consulted for further background information. Based on the comparative tests and the mentioned achievements, this recommendation is presented with the aim of promoting the application of the TC research results.

2 Scope and applications

This recommendation provides a test method for evaluating performance of concrete subjected to uniaxial compression or uniaxial tension and controlled carbonation under natural or accelerated conditions. It was developed based on a comparative carbonation test with CO_2 concentrations of 2% or 20%, but could be applied in case of other CO_2 concentrations as well. This procedure was evaluated in concrete with or without supplementary cementitious materials such as fly ash and ground granulated blast-furnace slag, with substitution volumes of up to 30 wt.% and 50 wt.%, respectively, but it is also applicable to other concretes with SCMs.

This recommendation fulfills the need for practices that allow accurate analysis and evaluation of the durability of concrete, and it will be helpful for research institutes and industries with an interest in the service life prediction of concrete structures.

While this recommendation focuses on the combination of uniaxial compressive/tensile load and carbonation, it can be extended to more complex loading schemes, for instance, carbonation under bending loads.

3 Equipment, specimens, and test procedure

3.1 Test equipment

3.1.1 Loading device

The compressive load is recommended to be applied on a prismatic concrete specimen using a test rig like that used for creep loading and described in the RILEM recommendation of TC 107-CSP [14]. A test rig that provides an external load by a hydro-pneumatic accumulator as demonstrated in Fig. 1a is recommended, while other test rigs that have the same principle and function and also fulfill the requirements of the recommendation of RILEM TC 107-CSP can be used to provide the uniaxial loading as well. The test

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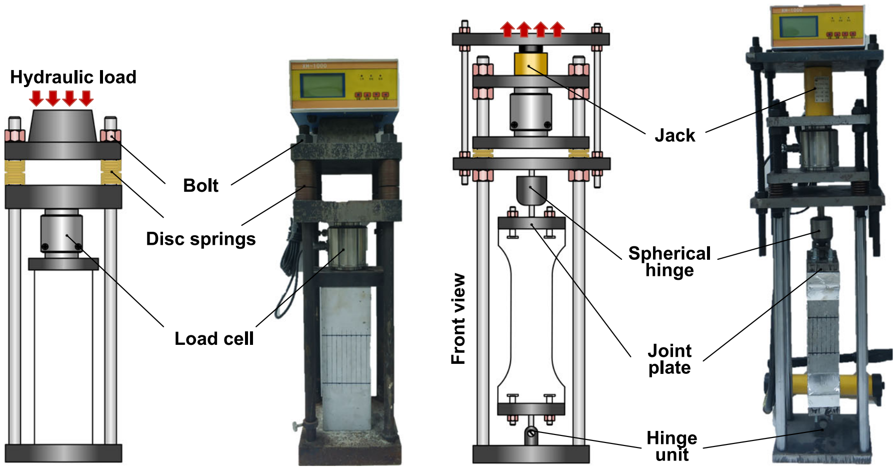


(a) Compression

(b) Tension

Fig. 1 Schematic representation (left) and the picture (right) of test rig for loaded concrete specimen

rig for uniaxial tension maintains the applied load by the "bolt & spring" method according to the recommendation of TC TDC-246 [1, 2], as shown in Fig. 1b. Load monitoring by a load cell is required to guarantee the stability of the external load during the entire test period.

3.1.2 Carbonation chamber

The carbonation chamber shall automatically adjust the inner environment and meet the specified requirements. The recommended test conditions as detailed in a specific standard for carbonation testing can be followed, e.g., a temperature of 21 ± 2 °C, a relative humidity of 60 ± 10%, and a CO_2 concentration of 1% according to EN 13295 [15]. The carbonation chamber should have sufficient internal space to accommodate at least one series of specimens vertically placed in the loaded rigs. For instance, a chamber with internal dimension of $1500 \times 860 \times 900\ mm^3$ is recommended to accommodate 18 specimens with compression or tension rigs, as shown in Fig. 1.

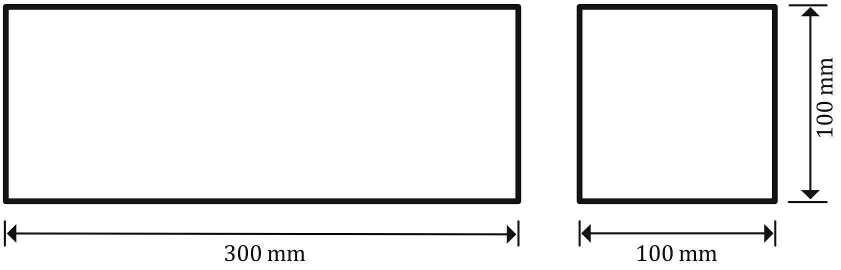
3.2 Specimens

Specimens need to be large enough to ensure a uniform stress distribution in the middle when subjected to uniaxial loads, and as the smallest dimension should be more than 3 times the maximum coarse aggregate size. In the meantime, the size of the loading rigs and their positioning in the carbonation chamber should be considered, which might limit specimen dimensions. The recommended specimen type is prismatic specimens with a cross-section area of $100 \times 100\ mm^2$ and a height of 300 mm for the test under uniaxial compression. Dumbbell specimens with a smaller cross-section of $70 \times 70\ mm^2$ are recommended for tension as well. The schematical representation for both is illustrated in Fig. 2.

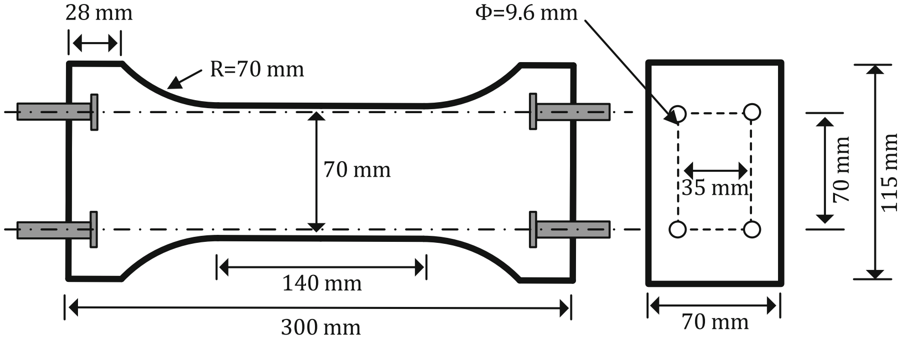
The tests at one specific CO_2 concentration and different designed load levels for one concrete mix are grouped into one series. The design load levels, expressed as a fraction of the average failure load are shown in Table 1. For one series, at least five load levels (− 0.6, − 0.3, 0, 0.3, and 0.6) are recommended for determining the influence of load on carbonation depth, where the negative values denote the compressive load condition, 0 denotes the condition without load which shall be also included as the reference and the positive values refer to tensile loading. One may also choose to only investigate the effect of either tension or compression. It should also be noted that, more load levels in compression would be needed to determine the transition load level for compression at which the effect of load changes from a microstructure densification which decreases the carbonation rate, to a microcrack formation which increases the carbonation rate. In contrast, the tensile load condition will always lead to an increased carbonation rate [13].

3.3 Test procedure

The test procedure can be divided into four parts and the outline is shown in Fig. 3.



(a) Prismatic specimen



(b) Dumbbell specimen

Fig. 2 Schematic representation of the top view (left) and side view (right) of the specimens used in compression and tension tests

Table 1 The recommended arrangement for one series of tests

Load level	Specimen shape	Specimen numbers
− 0.6	Prism	3
− 0.3	Prism	3
0	Prism	3
0.3	Dumbbell	6
0.6	Dumbbell	6

The load level is expressed relative to the strength as described in Sect. 3.3

3.3.1 Casting

The specimen is recommended to be cast according to EN 12390-2 [16] or another standard valid in the place of use, and all specimens are cast horizontally and compacted on a vibrating table. A layer of Teflon (Polytetrafluoroethylene, PTFE) (foil or thin sheet) is recommended to be put into the mold before casting to avoid the disturbing effect of demolding oil. If not otherwise specified, the slump of concrete is recommended to be controlled at around 110 ± 10 mm for easy casting.

3.3.2 Curing

The following three-step curing procedure is recommended, and the details not addressed here can be referred to EN 12390 [16]:

(i) The cast fresh specimen is recommended to be covered with a plastic sheet and placed in the curing room maintained at 20 ± 2 °C for 24 ± 0.5 h.
(ii) The demolded specimen is recommended to be soaked in a saturated calcium hydroxide solution or in a climate chamber at > 95% RH at 20 ± 2 °C for 28 days.
(iii) The specimen is then recommended to be preconditioned in a climatized room maintained at the same temperature and RH that will be applied during the carbonation test for 14 days [12]. Alternatively, a longer curing time can be chosen to allow the SCM reaction to occur to a larger extent and realize a microstructure that is more representative of the actual microstructure during the lifetime

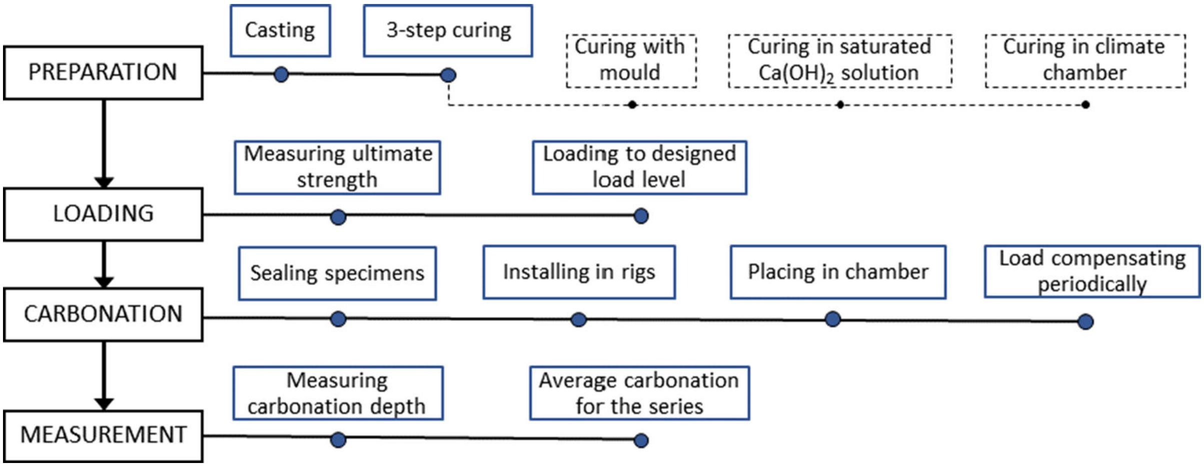


Fig. 3 Outline of the test procedure

of the concrete elements. Furthermore, longer preconditioning contributes to a uniform humidity throughout the concrete matrix.

In the end, the remaining lime solution on the specimen surfaces (if any) is recommended to be removed with a dry tissue.

3.3.3 Compressive strength & tensile strength

The compressive and tensile strength shall be determined on specimens with the same dimensions as those used for the carbonation test under sustained loads, i.e., prismatic specimens for the compressive strength and dumbbell-shaped specimens for the tensile strength. The strength of the specimens shall be measured on at least three samples for compression and six samples for tension, all at an age of 91 days after curing as described above. The procedure is recommended to be in accordance with the EN 12390 [16]. A servo-hydraulic test machine with an accuracy of 0.1 kN and a loading rate of 0.6 ± 0.2 MPa/s is recommended to be used. The obtained ultimate strength is used as the reference to determine the design load value at different load levels for the carbonation test under sustained loads.

3.3.4 Sealing specimens

The specimens for the carbonation test need further preparation to ensure a one-dimensional carbonation. After the curing procedure, two opposite side surfaces (troweled surface and bottom surface during casting) and the two end surfaces should be immediately sealed with a layer of self-adhesive aluminium foil, leaving only the other two opposite side surfaces to be carbonated. An illustration is shown in Fig. 4. In this way, two-dimensional carbonation in the corners and any effects of the casting direction as discussed below could be avoided.

3.3.5 Loading

The sealed specimen should be properly centered in the loading rig and loaded to the designed load level. Vertical placement of the test rig is recommended to avoid uneven distribution of stress caused by horizontal placement. Then the test rig with the installed specimen shall be mechanically loaded under uniaxial compression/tension up to the design load value by a universal testing machine or a loading jack. The design load value is determined by the ultimate strength and the chosen load level. Load monitoring and regular load compensation is recommended with a frequency depending on the design value of the applied load level based on the experimental results. Experimental results have indicated that the load should be adjusted at least every 5 days, 9 days, and 15 days, respectively, for a C30 prismatic concrete with compressive strength of 34.4 ± 0.8 MPa with design load levels of 30%, 45%, and 60%, to avoid more than 10% load deviation.

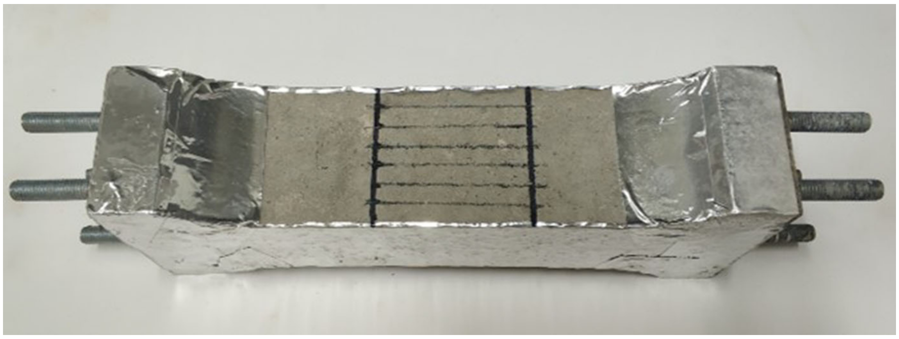


Fig. 4 An illustration of aluminium-foil-sealed tension specimen

3.3.6 Accelerated carbonation

The loaded specimen together with the test rig is recommended to be moved into a carbonation chamber with a temperature, a relative humidity and a constant CO_2 concentration as specified in the standard used. The temperature, relative humidity, and CO_2 concentration should be monitored during the whole period of the experiment.

Regarding the test procedure, it should also be noted that the raw materials, mix composition of concrete, curing procedure and the carbonation test condition can be adjusted to simulate the situation on-site better. Load levels in addition to 0%, 30%, and 60% can be also added according to the practical specifications.

4 Measurement and calculation

4.1 Measurement of carbonation depth

The measurement method is based on the EN 14630 [14]. The carbonated prism or dumbbell specimens are to be split in the middle with a universal testing machine creating a fresh surface, where dust and lose particles are recommended to be cleaned by any non-destructive method, such as slowly wiping with soft brushes or gently blowing with low-velocity blow gun. Then a colour indicator solution with a colour switch around a pH value of 10 (e.g. 1 g phenolphthalein in 70/30 vol.% ethanol/water) should be sprayed on the split surface to determine the carbonation depth after one hour or longer to avoid the leaching of the alkaline pore solution and get a better distinguishable colour change boundary.

The measuring points should be evenly distributed along the edges of the split surface. It is recommended to divide the edges of the two opposite carbonated side surfaces into ten equal parts and take measurements at the nine dividing points. The thickness of the colourless zone at each measuring point (in the case of a phenolphthalein colour indicator) is taken as the local carbonation depth, d. It is recommended to measure d perpendicular to the surface of the prism or dumbbell specimen using a ruler or a sliding gauge and a magnifier.

4.2 Calculation of the average carbonation depth of a single specimen

The average carbonation depth for each specimen, D_{cs}, is thus determined based on the results at all 18 measuring points, as shown in Eq. 1.

$$D_{CS} = \frac{1}{n}\sum\nolimits_{i=1}^{n} d_i \tag{1}$$

D_{CS}: the average carbonation depth; n: the number of measuring points; d_i: the carbonation depth of the measuring point i;

It should be noted that since the aggregate particles will not be coloured by indicators, a theoretical carbonation front at the intersection of the location point and a straight line connecting the limits on each side of the particle shall be used when measurement points coincide with dense aggregates. The extreme carbonation depth when encountering air voids or porous aggregates shall be treated depending on its local increment in accordance with EN 14630 [17] as well.

4.3 Calculation of the average carbonation depth of one series of specimens

After D_{CS} is determined for each specimen, the carbonation depth for each series shall be determined by averaging the D_{CS} of replicate specimens (at least three for compression and six for tension), denoted as D_{CLoad}. The standard deviation (SD_{DCLoad}) and the standard error (SE_{DCLoad}) on the average, D_{CLoad}, can be calculated by Eqs. 2 and 3, respectively, and reported for showing the variability in the test dataset.

The test report for one series of concrete is demonstrated in Table A2. The effect of load on the carbonation depth can be subsequently determined by fitting method based on the values of D_{CLoad} from one series of specimens.

Standard deviation:

$$\mathrm{SD}_{\mathrm{DCLoad}} = \sqrt{\frac{\sum_{j=1}^{m}\left(D_{\mathrm{CS}j} - D_{\mathrm{CLoad}}\right)^2}{m-1}} \tag{2}$$

Standard error:

$$\mathrm{SE}_{\mathrm{DCLoad}} = \sqrt{\frac{\sum_{j=1}^{m}\left(D_{\mathrm{CS}j} - D_{\mathrm{CLoad}}\right)^2}{m\cdot(m-1)}} \tag{3}$$

D_{CS_j}: the carbonation depth of replicate sample j; D_{CLoad}: the average carbonation depth of all the replicate samples at one single load level; m: the number of replicate samples.

The result can also be presented as the average value with its 95% confidence interval: $D_{CLoad} \pm 1.96\ SD_{DCLoad}$.

5 Test report

The test report shall contain at least the following information:

(1) Properties of concrete specimens (mix design and compressive strength).
(2) Curing conditions (temperature, RH, time).
(3) Information on the loading device and the carbonation chamber.
(4) Number and size of specimens.
(5) Load levels.
(6) Carbonation environment (temperature, RH, CO_2 concentration; with their variability).
(7) Test records and results filled in forms as Appendix A. One example is shown in Appendix B.
(8) Any deviation from the procedure described in this method.

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