



Accelerated carbonation tests for the probabilistic prediction of the durability of concrete structures



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HIGHLIGHTS

- Our approach combine direct use of experimental results, a carbonation model and a Bayesian network.
- The duration of experiments complies with a real engineering design process.
- The design of the concrete cover is full probabilistic.
- Rational criteria are used in combination for assessing the quality of successive updates.
- Standard recommendations and rules are accounted for from deterministic and probabilistic viewpoint.

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ABSTRACT

This paper proposes an efficient approach based on Bayesian networks for designing the cover of CEMI-based concrete structures for a prescribed durability under carbonation exposure. The approach combines the use of a carbonation model, whose correlated parameters are the nodes of a Bayesian network, and an experimental investigation on accelerated carbonation tests under high pressure (50% atmospheric pressure), the results of which allow the distributions to be updated. Several updates are performed at 5 days, 7 days and 10 days of exposure. The reliability-based design of cover is subsequently carried out using posterior distributions selected on the basis of the Bayes factor and the maximum likelihood criteria. Percentile values of the carbonation depth resulting from measurement and output of the model are compared, underlining the interest of the approach, which is valuable for practical considerations in engineering design.

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1. Introduction

Concrete structures tend to deteriorate over time. Among numerous sources of degradation, the carbonation of concrete is likely the most frequent because it results from the natural exposure of the concrete surfaces to the atmosphere. Carbonation leads to a decrease of the pH of the pore solution to below 9, thus reducing the concrete's ability to protect the embedded reinforcing bars from corrosion. In order to prevent the initiation of corrosion due to carbonation, a minimum concrete cover thickness is prescribed in European standards [1], considering exposure conditions and minimum specifications on the concrete strength. In addition, some specific requirements for the so-called durability indicators, such as the diffusivity of concrete, may be suggested [2]. Similarly to the mechanical tests for estimating the concrete strength,

accelerated carbonation tests can be used to assess the coefficient of diffusion of carbon dioxide, or alternatively the carbonation resistance [3] defined as the ratio of the binding capacity of carbon dioxide over the diffusion coefficient. However when using the carbonation resistance a major drawback is that the relationship between the carbonation resistance under accelerated condition and that under atmospheric condition is rather uncertain [3,4]. A simplified procedure for an engineering daily practice has been recently proposed [5], based on a linear regression between the inverse carbonation resistance obtained under natural and then accelerated carbonation, in the same concrete cores drilled from the surface of real structures. The procedure allows a minimum carbonation resistance to be prescribed according to a semi-probabilistic approach calibrated by means of Monte-Carlo simulations for a predefined Cornell reliability index. This approach is promising as a whole. Nevertheless, due to the weak correlation coefficient existing between natural and accelerated inverse carbonation resistances (less than 0.50) the derived relationship is

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questionable. Moreover the procedure has been calibrated for CEM I-based concretes and for a specific accelerated carbonation test (5% CO₂ partial pressure). Finally, the global uncertainty of the predicted carbonation depth is not really addressed in a probabilistic framework.

In order to efficiently benefit from accelerated carbonation tests avoiding the use of an uncertain relationship between natural and accelerated carbonation resistance, it is necessary to resort to a carbonation model capable of taking appropriate account of the high pressure of carbon dioxide applied during the test. High pressure conditions are indeed expected to modify the carbonation phenomenon in such a way that the amount of reacting hydrated compounds in the concrete is increased. Thanks such a model it becomes possible to estimate the coefficient of diffusion by comparing the measured and calculated carbonation depths.

In the context of a rational prediction of the durability of concrete structures and due to fact that concrete properties, geometrical parameters and environmental variables are uncertain, an important outcome of the accelerated tests would be the probabilistic assessment of the time to depassivation of steel, which can be useful during design and for the maintenance strategy [3,6,7].

In the present study, concrete specimens were cast and then tested. The carbonation depth under accelerated conditions was measured after several short exposure times and compared with the predictions of a carbonation model taking the applied carbon dioxide pressure into account. This comparison was made in the framework of a Bayesian approach using a specific model validation metric [8]. A Bayes network was employed in this study, with correlated nodes representing the main parameters of the carbonation model, and uncorrelated nodes enabling correlations to be introduced via intermediate models. Correlations and distributions were simultaneously updated at 5, 7 and 10 days of exposure to carbonation. Processing at three successive updates gave the opportunity to choose, among the posterior distributions, those that would be integrated in the subsequent probabilistic durability analysis and design. This choice was supported by the Bayes factor together with the maximum likelihood criterion. After the model validation stage, the distribution of the time to depassivation was assessed by Monte Carlo simulations. Considering a given percentile of the distribution, according to some design recommendations, it was possible to propose a cover depth complying with the prescribed durability specification. The present paper is divided into four sections. The first section summarizes the experimental investigation. The second describes the carbonation model. Results of the Bayesian approach are provided in the third section. The fourth and final section focuses on practical applications in the context of cover design with regard to the carbonation problem.

2. Experimental investigation

The aim of the experimental investigation was to characterize the onset of natural corrosion of steel reinforcing bars embedded in concrete exposed to carbonation. Previous experimental works have pointed out that reinforcement may be depassivated even when the concrete cover is not entirely carbonated [9]. In order to confirm these findings, it was decided to consider two states of carbonation of the concrete cover: complete carbonation (identified by a probability greater than 95% for a cover of 15 mm) and partial carbonation (corresponding to a probability around 50% for a cover of 30 mm). Hence, the carbonation model was used in a probabilistic context for a dual purpose: to support a durability design for a concrete structure and to estimate the time of exposure in the carbonation chamber, with a given probability for the cover to be carbonated.

2.1. Specimens and measurements

The concrete mix proportions in Table 1 [10] comply fairly well with the minimum requirements regarding the exposure class XC1 [11]. The water/cement ratio is slightly elevated compared to the maximum recommended value (0.72 instead of 0.65) in order to obtain transfer properties of the concrete enabling significant onset

Table 1
Concrete mix (CEM I 52.5 R cement).

Constituent	Units	Proportion
Cement	kg/m ³	295
Sand	kg/m ³	989
Gravel	kg/m ³	792
Water	kg/m ³	212

of natural corrosion within a few months (which was another objective in [10]). The specimens were cylinders of 100 mm in diameter and 50 mm in height.

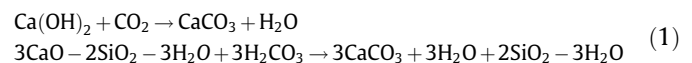
After a wet curing of 7 days, a drying-out at 60 °C such that the average saturation degree was roughly in balance with the relative humidity of the carbonation chamber and a pre-conditioning period of 28 days at 65% RH and 20 °C, the concrete specimens were exposed to a high carbon dioxide pressure (50% atmospheric pressure) in a controlled carbonation chamber with relative humidity of 65% ± 5% and temperature of 20 °C ± 0.5 °C. Two average carbonation depths in radial direction were measured by sample, each along the diametrically opposite edges of the freshly broken surfaces of split specimens. Measurements were carried out after the phenolphthalein spraying on surfaces at 5, 7 and 10 days of exposure, avoiding aggregates and out of the 10 mm-thickness layers located at both ends of the specimens.

2.2. Results of experiments

Results of the observations (two per sample) reported in Figs. 1–3 exhibit somewhat spread histograms, especially at 5 days of exposure, that is confirmed in Table 4 by mean values and standard deviations. The impact of measurement uncertainties is all the more visible since the carbonation depth is small. Nevertheless the average carbonation depth remains fairly linear with respect to the square root of time, which is a well known feature of this phenomenon. The average carbonation rate is about 3.8 mm/d^{0.5}: this is a rather high value but it does not differ significantly from values encountered in literature for concretes with elevated water porosity (15%).

3. Carbonation model

Carbon dioxide penetrates into non-saturated pores of concrete, dissolves in the pore solution and reacts with hydrated compounds (mainly portlandite and C–S–H gel) according to the global chemical balance equations:



Carbonation is a non-linear diffusion phenomenon of carbon dioxide with a strong sink term due to its nearly immediate consumption in the pore solution (reaction of carbonate ions with calcium ions). Elementary carbonation models assume that all the carbon dioxide consumption occurs at the ingress front, which provides the well known and practical analytical solution proportional to the square root of time, used, for example, in [3,10]. It is required for using these models to estimate natural resistance to carbonation, defined as the ratio a_0/D_0 where a_0 is the amount of carbonatable material and D_0 is the diffusion coefficient of CO₂. An empirical factor is usually employed for this purpose, allowing

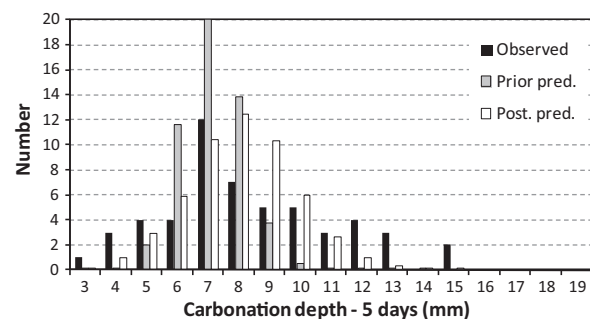


Fig. 1. Histogram of carbonation depth at 5 days.

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