Effect of Climatic Conditions on Carbonation of Concrete Structures

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Abstract. *Carbonation-induced corrosion is a degradation processes, which causes significant economic losses to the operators of an aging large, reinforced concrete (RC) structures such as cooling towers. Due to large variability of basic variables, the probabilistic approach is suitable to describe carbonation ingress. In this study, the probabilistic model is developed for service life assessments of large RC structures exposed to environmental effects. For existing structures, carbonation ingress in normally described using carbonation depth data from in-situ surveys. The shape of a time-dependent carbonation depth curve, essential for long-term predictions, is expressed through the weather function which accounts for the effect of environmental exposure of the structure. This study indicates how a probabilistic model of carbonation ingress can be established; numerical illustration is focused on existing cooling towers located in the Czech Republic. It appears that when long-term observations of carbonation depth are unavailable, the shape of a time-dependent carbonation depth curve can be determined on the basis meteorological data.*

Keywords

Carbonation, cooling towers, probabilistic assessment, climatic conditions.

1. Introduction

The construction industry is experiencing the increase in activities related to assessing and retrofitting buildings and bridges, contributing to the sustainable construction by extending the use of existing structures [1]. Reinforced concrete (RC) structures and their actual reliability are currently receiving considerable attention as a significant number of these structures reach their design service life. Carbonation-induced corrosion is one of major degradation mechanisms in the case of large RC structures and directly affects their service life. Cooling towers, industrial chimneys, or tunnels are examples of engineering works whose surfaces are directly exposed to adverse climatic conditions and whose service life is often dominated by carbonation ingress and subsequent development of corrosion [2].

Degradation processes of concrete structures are commonly modelled as two-phase processes, including the initiation and propagation phases. According to the current practice, the serviceability limit states (SLS) and ultimate limit states (ULS) are considered to define service life of the structure. Since modelling a corrosion propagation phase is associated with large uncertainty, the initiation limit state (ILS), related to the corrosion of reinforcement initiation, is identified, and is defined as time when the carbonation front reaches the concrete cover depth.

As the probabilistic model of concrete cover depth can be relatively easily obtained from measurements, modelling of the carbonation depth appears to be a key issue of the probabilistic analysis of corrosion initiation [3], [4]. This is why the study demonstrates how a probabilistic model of carbonation ingress can be established on site- and structure-specific data. Numerical example is focused on analysis of existing cooling towers located in the Czech Republic.

2. Uncertainties Affecting Carbonation Ingress

Carbonation models are mostly based on the diffusion of CO_2 in the pore system of concrete. The rate of carbonation progress depends on many parameters such as concrete permeability, the ambient temperature, relative humidity, and carbon dioxide content in the air. Concrete cover permeability further depends on the concrete mix type and composition, the aggregate gradation and the processing and curing of the concrete mix [5]. All these parameters are included in the model provided by *fib* MC2010 [6]; see also [7] for further details.

Uncertainties in the individual basic variables can be adequately described by probabilistic models. Significant uncertainty is particularly associated with parameters related to concrete diffusion properties. Information about the permeability of concrete related to its material parameters seems to be crucial. For example, the carbonation model described in the IAEA guideline [8], intended for practical assessments of existing RC structures, is based only on the water to cement ratio *w/c* – a key factor affecting diffusion properties of concrete.

3. Selected Models for Carbonation Depth

3.1. Model in CEB Bulletin 238

Most carbonation models are based on the relationship between carbonation depth x_c (usually in mm) and the time since construction t (in years). CEB bulletin 238 [9] provides the fundamental relationship:

$$x_c(t) = At^{0.5-n}, \tag{1}$$

where A is the carbonation rate (carbonation depth after the first year of exposure) and n is an exponent dependent on climatic conditions.

Values of n may generally range from 0 up to 0.5. The most simplified model considers $n = 0$:

$$x_c(t) = A\sqrt{t}. \tag{2}$$

In determination of carbonation rate A, various levels of approximation can be applied; their use is generally conditioned by available information about the input variables. Some variables on which rely the physical models of the carbonation process such as diffusion properties of concrete related to a *w/c*-ratio are difficult to specify in assessments of existing structures. A reasonable approach is then to determine carbonation depth from in-situ measurements. Using Eq. (2), the distribution of A is obtained from measured x_c-values as:

$$A = [t/x_c(t)]^2. \tag{3}$$

However, simple relationship (2) fails to account for site-specific microclimatic effects. These are commonly considered by a weather function $W(t)$ that describes the effect of wetting events that partly inhibit ingress of CO_2 [10]; see Section 3.2. Importance of this effect increases with time of exposure. Relationship (2) may thus provide crude estimates only.

3.2. *fib* Model

Detailed analytical model for carbonation depth is provided by *fib* MC 2010 [6] and *fib* Bulletin 34 [11]:

$$x_c(t) = \sqrt{2k_e k_c R_{\mathrm{NAC},0}^{-1} C_{\mathrm{CO2},s}}\sqrt{t}W(t), \tag{4}$$

where:

- k_e denotes the environmental function accounting for the influence of humidity on the diffusion coefficient,
- k_c is the execution transfer parameter dependent on the influence of concrete curing,
- $R_{\mathrm{NAC},0}^{-1}$ is the inverse carbonation resistance of concrete determined in natural conditions at reference time t_0 (commonly at 28 days),
- $C_{\mathrm{CO2},s}$ is the concentration of CO_2 in the ambient air commonly in kg/m^3,
- and $W(t)$ is the weather function discussed below.

The basic variables in the *fib* model can be described on the basis of commonly available information apart from the concrete permeability expressed through the inverse carbonation resistance $R_{\mathrm{NAC},0}^{-1}$, which should preferably be derived from in-situ carbonation depth measurements or material tests on specimens taken on the existing structure.

The weather function considers the microclimate conditions to which the concrete surface is exposed:

$$W(t) = \left(\frac{t_0}{t}\right)^{\frac{(p_{\mathrm{sr}} \times ToW)^{b_{\mathrm{w}}}}{2}}, \tag{5}$$

where t_0 denotes the reference time when $R_{\mathrm{NAC},0}^{-1}$ is determined, ToW is the time of wetness, p_{sr} is probability of driving rain, and b_{w} is the regression coefficient.

The time of wetness is probability of occurrence of a rainy day, determined from an average number of rainy days per year, $n_{\text{rainy day}}$:

$$ToW = \frac{n_{\text{rainy day}}}{365}, \tag{6}$$

Day is considered as rainy when precipitation water is ≥ 2.5 mm.

Probability of driving rain represents the average distribution of the wind direction during rain events. For indoor (sheltered) structural members, $p_{\mathrm{sr}} = 0$ applies. For outdoor structural members, $p_{\mathrm{sr}} = 1$ can be considered for horizontal members. For vertical outdoor structural members, a p_{sr}-value should be evaluated from the nearest weather station data.

The exponent b_{w} can be specified by regression; see Section 4.1 for further discussion.

Considering Eq. (5), relationship (4) can be rewritten as:

$$x_c(t) = \sqrt{2k_e k_c R_{\mathrm{NAC},0}^{-1} C_{\mathrm{CO2},s}}\sqrt{t}\left(\frac{t_0}{t}\right)^{\frac{(p_{\mathrm{sr}} \times ToW)^{b_{\mathrm{w}}}}{2}}, \tag{7}$$

$$x_c(t) = \sqrt{2k_e k_{\mathrm{w}} k_c R_{\mathrm{NAC},0}^{-1} C_{\mathrm{CO2},s}} \times t^{0.5-\frac{(p_{\mathrm{sr}} \times ToW)^{b_{\mathrm{w}}}}{2}}, \tag{8}$$

where $k_{\mathrm{w}} = t_0^{(p_{\mathrm{sr}} \times ToW)^{b_{\mathrm{w}}}}$ denotes the coefficient accounting for the microclimate effect on concrete at the reference time t_0.

Comparison of the fundamental relationship (1) with the *fib* model (8) reveals that:

- The carbonation rate A should cover the effects of humidity, execution, carbonation resistance of concrete, exposure to CO_2, and partly also of local climate expressed through ToW, p_{sr} and b_w, while
- The exponent n in Eq. (1) depends only on the effect of local climate, $n = (p_{sr}\ ToW)^{bw} / 2$.

4. Numerical Illustration

Development of the probabilistic model for carbonation is demonstrated using the database of measurements on existing cooling towers (CTs) located in the Czech Republic. Carbonation depth measurements were collected by Holický and Holická [3] from ten CTs at age of 10 to 40 years. The measurements were taken from external surfaces of shells as they are sensitive to carbonation ingress due to their exposure and often insufficient thickness of concrete cover. Subsequent corrosion may then be the major factor affecting service life of the whole CT.

Considering the fundamental relationship (1), a sufficiently long time series of carbonation depth measurements is needed to derive both carbonation rate A and exponent n specifically for the existing structure, using measurements only. As the exponent n depends only on the effect of local climate (Section 3.2), local meteorological data can be utilised to estimate its value.

In contrast, the carbonation rate A primarily accounts for a largely structure-specific effect of diffusion characteristics of concrete that can scarcely be estimated without advanced material tests. When an n-value is estimated from meteorological data, the probabilistic distribution of A can be derived from available measurements of carbonation depths.

4.1. Exponent *n*

Following these arguments, a representative value of the exponent n is initially derived, considering characteristic climate in the industrial areas of the Czech Republic.

Time of wetness ToW is a deterministic parameter. For European climates, ToW is likely to range in the interval 0.1-0.3 (0.1-0.2 for Spain and Portugal, 0.2 – 0.3 for the UK, Netherlands, Germany, Norway and Denmark) [10]. In the Czech Republic, $ToW \approx 0.13$ can be considered for the industrial areas in the lowlands in Northern Bohemia [4].

The usual range of probability of driving rain is $p_{sr} \approx$ 0.1-0.6 for vertical structural members [10]. Based on meteorological measurements, the analysis of wind conditions in the Czech Republic was performed by Sobíšek [12] where characteristic areas with the occurrence of certain typical distributions of wind directions were identified. A typical wind distribution, which corresponds to the wind conditions in a large part of Bohemia including the industrial area under consideration, is plotted in Fig. 1. It is characterized by a markedly prevailing westerly wind direction with a secondary peak towards the east.

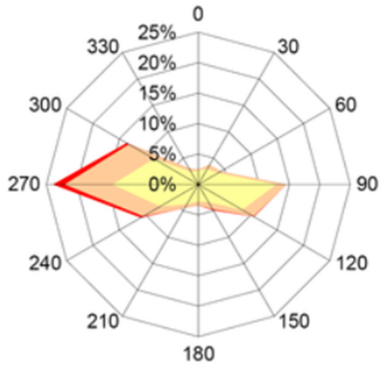

Fig. 1: Wind distribution under consideration.

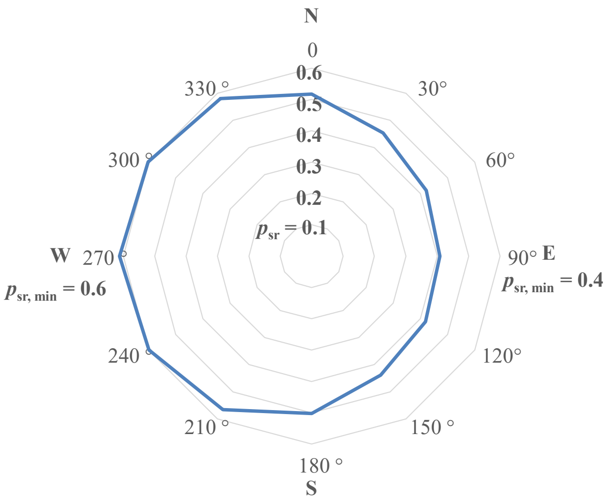

Fig. 2: Probability of driving rain derived from wind distribution.

Probability of driving rain obtained from the wind distribution in Fig. 1 is shown in Fig. 2. Note that this is a rather simplified estimate since the combination of rain and wind effects in a certain direction is assumed and, as the shell is vertical, its wetting on the windward side only is assumed. Part of the rotating hyperboloid is likely wetted even when rain occurs in the absence of wind. Since the analysis is normally focused on the whole shell, it is mostly reasonable to consider the average value, $p_{sr} = 0.5$.

When a time series of carbonation depth measurements is available, μ_{bw}—mean of exponent b_w—can be determined by regression. In the absence of data, the estimate, $\mu_{bw} = 0.446$, based on the analysis of measurements described in [13], [14] can be considered as recommended in the *fib* documents [6], [11] and in the JCSS Probabilistic Model Code [15].

The parameters p_{sr}, ToW, and μ_{bw} provide the best estimate – expected value of the exponent n for the climatic conditions under investigation:

$$n \approx (0.5 \times 0.13)^{0.446} / 2 = 0.15. \quad (9)$$

Estimate (9) well matches with general knowledge about the exponent n. According to CEB Bulletin 238 [9], n is expected to attain zero in indoor conditions while $n = 0.3$ is characteristic for unsheltered outdoor conditions.

Fig. 3 reveals a significant effect of the exponent n for long-term predictions of carbonation ingress. Mean carbonation depths, $\mu_{xc}(t)$, as a function of time of exposure, t, are displayed for selected values of the exponent (for a representative carbonation rate $A = 2.8$ mm/y$^{0.5-n}$; see Section 4.2). It appears that after 40 years of exposure (common design service life of CTs), mean carbonation depths are expected to vary in a broad range – from about 5 mm up to nearly 20 mm. The value $n = 0.15$ based on meteorological data leads to $\mu_{xc}(40\text{y.}) \approx$ 10 mm.

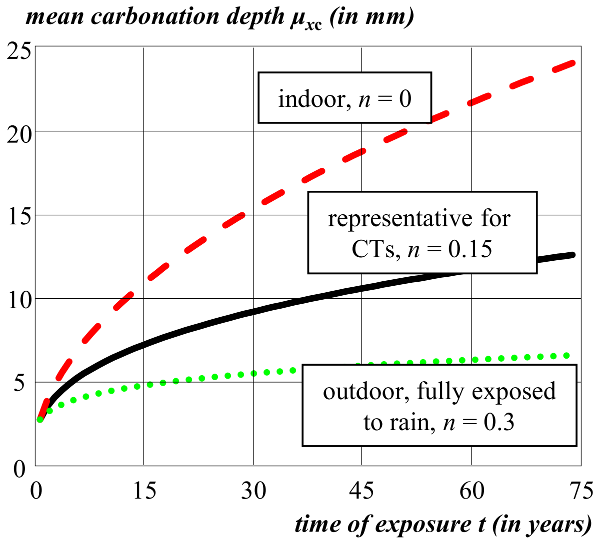

Fig. 3: Mean carbonation depth as a function of time of exposure for selected values of exponent n (for representative carbonation rate $A = 2.8$ mm/y$^{0.5-n}$).

Uncertainty related to the time development of carbonation ingress can be characterised by considering variability of b_w; coefficient of variation $V_{bw} = 36.5$ % can be considered [15].

4.2. Carbonation Rate *A*

In the absence of structure-specific data, a first approximation of the carbonation rate may be based on the generic information provided in the literature. Referring to the left term in Eq. (8) and considering $n = 0.15$, the following can be taken into account:

(1) According to [10], the effect of concrete diffusion properties and CO_2-concentration can be merged into a single parameter $k_{NAC} = \sqrt{(2\, R_{NAC,0}^{-1}\, C_{CO2,s})}$. For different types of cement and various w/c-ratios, k_{NAC}-values were found to vary from 2 to 8 mm/year$^{0.5}$.

(2) Considering characteristic weather conditions and engineering practice in the Czech Republic, Mlčoch [4] obtained:

- $k_e = 0.7$ for a mean annual relative humidity of 75 %,
- $k_c = 1$ for time of curing of 7 days.

For:

$$k_w = t_0^{(p_{sr} \times ToW)^{b_w}} = 0.0767^{0.30} = 0.46 \text{ y}^{0.3}, \quad (10)$$

with $t_0 = 28\text{d} = 0.0767\text{y}$, the following estimate of carbonation rate is obtained:

$$A_{fib} = k_{NAC}\sqrt{k_e k_w k_c} = \\ = (2 \; to \; 8) \times \sqrt{0.7 \times 1 \times 0.46} = \\ = 1.1 \text{ to } 4.5 \text{ mm/y}^{0.35}. \quad (11)$$

This range is wide and in service-life assessments, it can be important to improve the estimate of A on the basis of carbonation depth measurements using Eq. (1). Fig. 4 displays the histogram of measured carbonation rates [3], fitted normal distribution, and 5% and 95% fractiles of distribution considering $n = 0.15$.

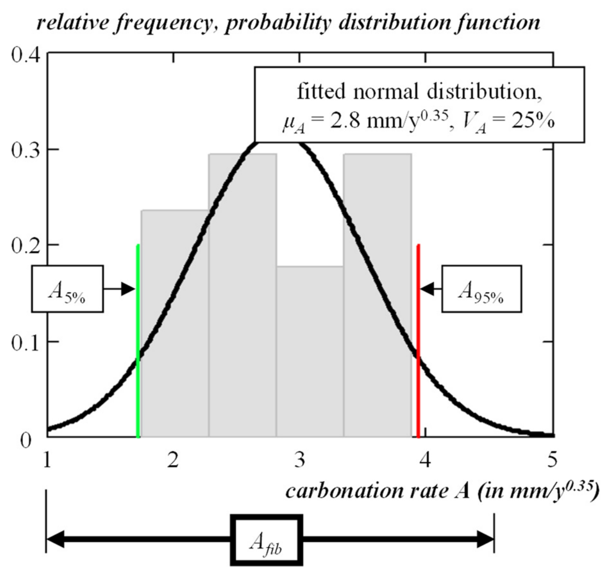

Fig. 4: Histogram of measured carbonation rates, fitted normal distribution, and 5% and 95% fractiles of distribution ($n = 0.15$).

The database in [3] provides a rather general information, covering a range of structures from different types of concretes, under various maintenance regimes exposed to various climatic effects. Despite this, the information in the database improves the estimate based on the A_{fib}-range as shown in Fig. 4.

When a probabilistic distribution of carbonation rate A is determined from carbonation depth measurements, the probabilistic model for $x_c(t)$ can be based on Eq. (8):

$$x_c(t) = A \times t^{0.5 - \frac{(0.5 \times 0.13)^{b_w}}{2}}, \quad (12)$$

where $p_{sr} = 0.5$ and $ToW = 0.13$ are the representative values obtained in Section 4.1, and b_w is described by a normal distribution with $\mu_{bw} = 0.446$ and $V_{bw} = 0.375$.

A representative coefficient of variation of carbonation rate is $V_A = 0.25$ and a lognormal distribution is commonly assumed [4].

Considering $\mu_{A,5\%} = 1.7\ \text{mm/y}^{0.3}$ and $\mu_{A,95\%} = 3.9\ \text{mm/y}^{0.3}$ for poor- and high-quality concretes respectively (Fig. 4), Fig. 5 displays carbonation depth as a function of time of exposure; the thin lines indicate the bounds of 75% confidence intervals. It follows that the quality of concrete significantly affects both magnitude and scatter of carbonation depths.

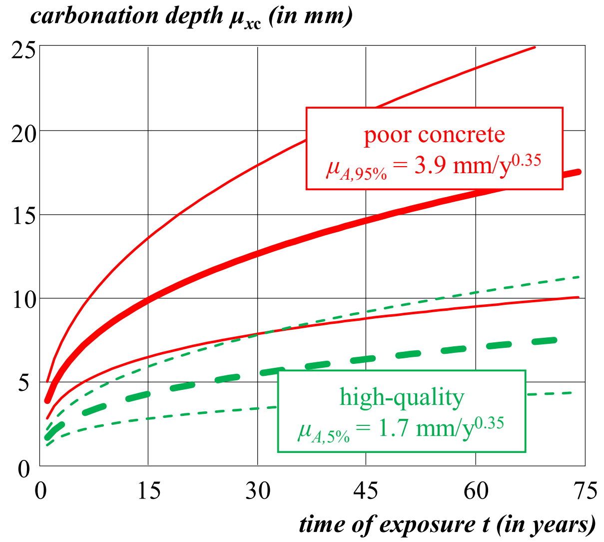

Fig. 5: Carbonation depth as a function of time of exposure for poor- and high-quality concrete (thin lines indicate bounds of 75% confidence intervals).

5. Conclusion

This study demonstrates how a probabilistic model of carbonation ingress can be derived on the basis of in-situ measurements and relevant meteorological data. The main findings are summarised as follows:

- The carbonation rate should cover the effects of humidity, execution, carbonation resistance of concrete, exposure to CO_2, and partly also of local climate.
- The exponent n in Eq. (1) primarily depends on the effect of local climate (wind-driven precipitations).
- In common situations, deriving the carbonation rate from measurements of carbonation depth is recommended.
- If a time series of carbonation depth measurements is unavailable, the exponent n—defining the shape of time-dependent carbonation depth curve—can be determined from the meteorological data according to Section 4.1 of this paper.

Numerical example is focused on the existing cooling towers located in the Czech Republic. It appears that:

- Carbonation is affected by precipitations. The general experience indicates that the time of wetness varies for European climates in the range from 0.1 up to 0.3; a value of 0.13 can be considered for the industrial areas in the lowlands in Northern Bohemia.
- For vertical structural members, it is further important to specify probability of driving rain; for the cooling tower under consideration this probability is determined as 0.6 for the windward surface and 0.4 for the leeward surface.

Modelling of carbonation ingress is a key step in the analysis of Initiation (Durability) Limit States that provides essential inputs for subsequent analyses of Serviceability and Ultimate Limit States [16].

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