Corrosion of concrete structures due to climate change

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2 Corrosion of concrete structures due to climate change

2.1 Scope of the study

Concrete is clearly one of the most predominant-used material in both residential and non-residential structures across Europe (Peled and Fishman, 2021). A reinforced concrete (RC) structure is expected to satisfy criteria for serviceability, structural integrity, and stability over its designed operational lifespan, without significant loss of utility or excessive unforeseen maintenance (for general requirements see also EN 1990). Comprehending the degradation mechanisms that impact these structures is essential for accurately estimating their service life and formulating cost-effective maintenance strategies. The main mechanisms responsible for concrete degradation include corrosion caused by carbonation and the presence of chloride ions, freeze-thaw cycles, sulphate attack and erosion due to high-velocity water flow, ice, or wind-blown sand.

Carbonation refers to the reaction between carbon dioxide in the air and calcium hydroxide in the concrete resulting in loss of alkalinity, thereby affecting the passivity of the reinforcing steel and making it susceptible to corrosion. This process is known as carbonation-induced corrosion. The initiation and progression of the carbonation-induced corrosion process are significantly influenced by environmental conditions. Temperature, atmospheric humidity and levels of carbon dioxide (CO_2) concentration serve as the main environmental factors influencing this degradation mechanism. The escalation in these environmental drivers is directly attributable to climate change and prevalent CO_2 emissions. The literature indicates an increase in corrosion depths due to carbonation ranging from 40-45% by the year 2100, as compared to the climate conditions observed in 2000, under the Representative Concentration Pathway 8.5 (RCP8.5) or equivalent A1FI scenarios (Talukdar et al. 2012b and 2013; Saha and Eckelman 2014; Peng and Stewart 2014; Mizzi et al. 2018). Consequently, the financial implications of augmented maintenance and repair costs are substantial, estimated to be in the range of hundreds of billions of dollars annually (Bastidas-Arteaga and Stewart, 2015). For a detailed discussion of the implications of climate change on the corrosion of reinforced concrete, the reader is referred to Sousa et al. (2020).

On the other hand, chloride-induced corrosion is caused when chloride ions penetrate the concrete and initiate corrosion of the reinforcing steel. The permeation mechanism for these ions is notably influenced by temperature and humidity conditions. Therefore, the chloride-induced corrosion process is similarly susceptible to alterations in climate conditions. For an updated review of the mechanisms of chloride-induced corrosion the reader is referred to Rincon et al. (2023). The existing literature reports increments of chloride concentration at the rebar-level depths ranging from 6-15% by 2100 when compared with the climate conditions in 2000 under the RCP8.5 or equivalent A1FI scenarios (Xie et al. 2018, Saha and Eckelman 2014). Notably, this corrosion type is predominantly observed in marine environments and in regions susceptible to snowfall, where the application of de-icing salts is routine. **Given the relatively limited geographical prevalence and comparatively lower impact of the chloride-induced corrosion, this report focusses on the carbonation-induced corrosion. For the remainder of this document, carbonation-induced corrosion will be referred to simply as corrosion.**

The studies on the impact of climate change on corrosion has mainly focused on civil infrastructures and there are only a few studies analysing its impact on the building stock. Saha and Eckelman (2014) found that, for around 60% of the existing RC buildings in the Boston metropolitan area, the penetration depths of carbonation will reach the rebar level by 2050 (A1FI scenario), while their service life will be reduced by 26 years by the end of the century. In Europe, Finnish buildings have been studied by Köliö et al (2014) and Pakkala et al (2019). They found that the corrosion rate during winter in the coastal region is expected to increase 200% for the facades facing to the South under RCP8.5 scenario.

The corrosion rate is influenced by several factors including geographical conditions, structural design in accordance with standards, material composition, age, and the effectiveness of inspection and maintenance strategies (Nogal et al, 2021). Geographical conditions, in particular, correlate with the effects of climate change, manifested in diverse temperature and relative humidity fluctuations across different regions. However, there is limited research on the impact of climate change on concrete deterioration in buildings across Europe and further investigation is required.

The following sub-section of this chapter provides an overview of the mechanism underlying carbonation-induced corrosion and examines the influence of different parameters in climate-induced variations. Then, the chapter discusses various corrosion models and evaluates their suitability for assessing the corrosion risk to the reinforced concrete (RC) building stock across Europe, considering future climate change scenarios.

Subsequently, the model adopted for the assessment of the carbonation depth is described in the last section of the chapter.

2.2 Mechanism of carbonation-induced corrosion influenced by climate change

Environmental parameters such as humidity, temperature, and carbon dioxide concentration, coupled with concrete-specific factors such as alkalinity and permeability, influence both the carbonation rate and its depth (Yoon and Chang, 2020; Parrot, 1999; Stefanoni, Angst and Elsener 2018). The carbonation process initiates at the concrete's outer layer, generating a front of decreased alkalinity that progresses with ongoing CO_2 diffusion and reaction. When the carbonation depth extends to the reinforcing bar (rebar) level, the phase transitions from corrosion initiation to corrosion propagation. During this latter stage, aggressive agents de-passivate the reinforcement, leading to a compromised state that fails to satisfy the structural safety, stability, functionality, and aesthetic requirements. While the carbonation initiation stage dominates the structural service life spanning several decades, the propagation typically lasts only a few years. The measure used to study the severity of the carbonation is the carbonation depth, which is quantified as the average distance from the concrete surface where alkalinity has decreased.

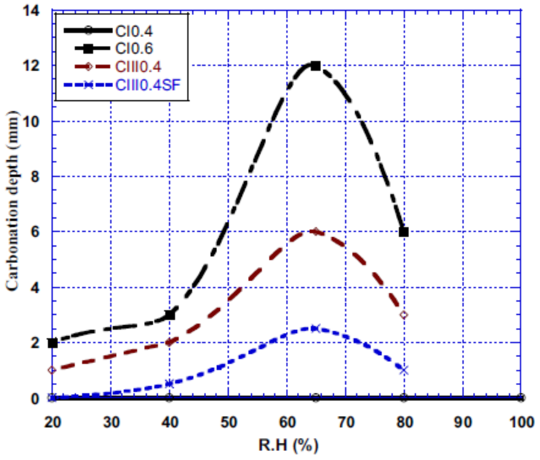
Climate change is inducing shifts in environmental temperatures and Relative Humidity (RH) levels. The extent to which climate change accelerates corrosion depends on the magnitude, direction, and range of these temperature and RH fluctuations. Several mathematical models have been proposed that capture the complex interplay between temperature and RH in the corrosion process (e.g., Stewart et al, 2011). The estimation of the impact on the corrosion rate according to these models can be determined through sensitivity analysis. This allows to make simplifications in the numerical analysis without a loss of credibility in the results.

Accordingly, various studies analyse the impact of climate change on the corrosion rate depending on the geographical location. Some studies consider the spatial variability with respect to the temperature, such as Talukdar and Banthia (2013) in locations in India, UK, USA, Canada and Australia, Mizzi et al (2018) in Malta and Bastidas-Arteaga et al (2022) in Portugal. Other research projects study the spatial variability caused by both, temperature and RH. For instance, Peng and Stewart (2014) study several locations across China and De Larrard et al. (2014) examined six different locations in France.

Many authors claim that relative humidity might influence significantly the carbonation depth (Parrott, 1994; ShieBl, 1997; fib, 2006; Yoon et al., 2007). A minimum relative humidity (RH) threshold of 30-50% is needed for carbonation reactions (Russell et al. 2001; Al-Khaiat and Fattuhi 2002). The maximum carbonation rate occurs at RH of 60-90% (Garces 2021; Ho and Lewis, 1987).

Elsalamawy et al. (2019) compared different models for the calculation of carbonation depth taking into account RH and compared the results with accelerated carbonation tests. Based on the results of such tests, for different cement types, the authors observed that the carbonation depth increased with the increase of RH to reach a peak value at 65% RH, independently of the cement type, as illustrated Figure 1**.**

Figure 1. Influence of RH in the carbonation depth (Elsalamawy et al., 2019).



Temperature also plays a role in corrosion speed, with higher temperatures promoting ion movement and lower temperatures causing condensation and higher humidity levels. The corrosion rate is, therefore, highly sensitive to changes in the environmental conditions.

Despite the crucial role of the RH in the corrosion process, the increments of carbonation depths observed in the above works, with and without the consideration of the RH, are of the same range, around 40-45% as mentioned before. This may be due to the relatively small variation in the RH according to the climatic projections in comparison with the large variation in temperature and CO_2 emissions. For instance, in Europe, increments of 4°C to 6°C are expected by 2100 in most European areas (RCP8.5) reaching 8°C to 10°C in the Northern regions. In contrasts, only minor variations are anticipated in terms of RH: 4% to 10% in some northernmost regions, while some Mediterranean countries could even experience a reduction of RH (Sousa et al., 2020). Note that, in some cases, a decrease in RH may reduce the corrosion rate. Nonetheless, the results are limited to the European context and specific mathematical models, and they should be approached with caution in locations with distinct climatic conditions.

The same trend was observed in a sensitivity analysis carried out by Bastidas-Arteaga et al. (2022). In this case, the expected range of variation of temperature and RH in three different locations in Portugal was analysed, observing the impact on the carbonation depth of reinforced concrete structures. The selection of the locations was made to obtain a wide variability in terms of temperature and RH. The results shown the importance of considering specific exposure conditions at a correct scale in the lifetime assessment, as for example, in some cases a decrease in RH variation was not enough to counterbalance the effect of the increment in temperature and CO_2.

Considering that for an accurate estimation a more detailed scale is required, this report does not analyse the effect of RH variation on the corrosion rate across Europe. Instead, it focuses on the projections of CO_2 levels and the temperature shifts due to climate change to assess potential changes in the corrosion depth, as detailed in the subsequent section.

2.3 Selection of model for assessment of carbonation depth

Concrete contains calcium hydroxide in pores due to the hydration reaction of C_3S tricalcium silicate ($3CaO{\cdot}SiO_2$) and C_2S dicalcium silicate ($2CaO{\cdot}SiO_2$) in cement, maintaining an alkaline environment with a pH of 12.5 to 13.0. Carbonation occurs when CO_2 gas diffuses into concrete, consuming calcium hydroxide and causing a decrease in pore solution pH. This can lead to reinforcement corrosion, reducing concrete's long-term durability. Calculating carbonation rate is crucial for predicting service life and CO_2 diffusivity (Yoon et al. 2020).

As already referred, the assessment of the impact of climate change is made in terms of the carbonation depth in reinforced concrete buildings, as this metric has been used extensively by many authors to predict the service life of structures. Different models are available in the literature for the quantification of the carbonation depth. Most widespread models are based on a static environment, but the aim of this study is to model reinforced concrete deterioration affected by spatially and temporally climate-dependent variables.

In the carbonation process, the time to corrosion initiation depends on many factors, such as concrete type and quality, concrete cover, relative humidity (RH), carbon dioxide (CO_2) concentration, among others. Among mathematical models that have been proposed in the literature over the years for the assessment of the carbonation depth in reinforced concrete structures, the most common approach is based on Fick's first law of diffusion. In this case, the carbonation depth, $x_c(t)$, increases as a function of the square root of time, as given by expression (1) (Yoon et al., 2007):

$$x_c(t)=K_c.\sqrt{t} \tag{1}$$

where $x_c(t)$ is the carbonation depth (in mm) at the time (t) of exposure (in years) to carbon dioxide, CO_2 and K_c is the carbonation coefficient (in mm/year$^{0.5}$) that reflects the influence of the environmental conditions and concrete quality. Over time, the rate at which carbonation occurs in waterproof concrete and humid environments decreases significantly, eventually becoming insignificant (Saura Gómez el al. 2023).

The carbonation model recommended by Yoon et al. (2007) takes into account a diffusion coefficient (D_{CO_2}), since carbonation depth is very much dependent on this coefficient as given by expression (2):

$$x_c(t)=\sqrt{\frac{2D_{CO_2}(t)}{a}C_{CO_2}.\,(t\text{-}t_0)} \quad (2)$$

where, C_{CO_2} is the mass concentration of CO_2 in the environment (kg/m^3); k_{urban} is a factor that takes into account the increased concentration of CO_2 in urban areas; a is a factor that takes into account cement characteristics, given by expression (4); t_0 is the initial year; n_m is the age factor for microclimatic conditions; and D_{CO_2} is a diffusion coefficient dependent on time and temperature,, given by:

$$D_{CO_2}(t)=D_1(t\text{-}t_0)^{\text{-}n_d} \quad (3)$$

where D_1 is the initial CO_2 diffusion coefficient, and n_d is the aging factor.

On the other hand, the factor 'a' in equation (2), taking into account cement characteristics is given by:

$$a=0.75C_e\times C_{CaO}\times\alpha_H\frac{M_{CO_2}}{M_{CaO}} \quad (4)$$

where, C_e is the cement content (kg/m^3), C_{CaO} is the calcium oxide content in the cement, M_{CO_2} is the molar mass of CO_2, M_{CaO} is the molar mass of CaO, and α_h is the degree of hydration, given by the following expression, as a function of the water to cement ratio (w/c):

$$\alpha_H\approx 1\text{-}e^{\text{-}3.38w/c} \quad (5)$$

As already referred, the above model does not take into account the value of RH explicitly.

The model described by expression (2) considers that CO_2 concentrations are time-invariant. However, to consider climate change, the increased concentration of CO_2 in the atmosphere should be taken into account and thus, CO_2 concentration should be modelled as non-stationary process in the calculation of carbonation depth (Stewart et al., 2002). Therefore, the model adopted for the calculation of carbonation depth, which is described in the following paragraphs, takes into account the temporal variability of CO_2 concentrations as suggested by Stewart et al. (2002). This model is a function of temperature and CO_2 concentration over time, does not take into account relative humidity and is corrected by a coefficient (k_{urban}) that takes into account the increased levels of CO_2 in urban environments (Saha and Eckelmann, 2014). Additionally, the model does not take into account the concrete strength. Hence, according to this model, the carbonation depth x_c over time t, in cm, is given by expression (6):

$$x_c(t)=\sqrt{\frac{2D_{CO_2}(t)}{a}k_{urban}\int_{t_o}^{t}C_{CO_2}(t)dt}\times\left(\frac{t_0}{t\text{-}t_0}\right)^{n_m} \quad (6)$$

where, C_{CO_2} is the mass concentration of CO_2 in the environment (kg/m^3); t_0 is the initial year; *a* is the factor that takes into consideration the cement characteristics, given by expression (4); n_m is the age factor for microclimatic conditions; and D_{CO2} is a diffusion coefficient.

The diffusion coefficient is dependent on time and temperature, given by:

$$D_{CO_2}(t)=f_T(t).D_{0,CO_2}(t\text{-}t_0)^{\text{-}n_{d,CO_2}} \quad (7)$$

where, $D_{0,CO_2}$is the initial CO_2 diffusion coefficient; $n_{d,CO_2}$is the aging factor; and $f_T(t)$ is the time-dependent temperature factor, given by:

$$f_T(t)\approx\exp\left[\frac{E}{R}\left(\frac{1}{293}\text{-}\frac{1}{273+T_{avg}(t)}\right)\right] \quad (8)$$

where E is the activation energy of the diffusion process; R is the universal gas constant; and $T_{avg}(t)$ is the running average temperature (°C) over the period of time ($t - t_0$).

The model expressed by (6) is the adopted model in the following calculations.