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Residual service life of carbonated structures based on site non-destructive tests

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ABSTRACT

Assessing the residual service life of carbonated reinforced concrete structures is typically conducted by measuring cover depths and carbonation of drilled cores, assuming the "square root law" for the progress of the carbonation front. Given the large spatial variability of carbonation depths, the required number of cores becomes prohibitive.

A model is presented, based on numerous experimental data, by which the carbonation rate can be estimated by means of non-destructive site measurements of the air-permeability kT. A Weibull distribution of the carbonation rate K_c is fitted to the results, which is a function of kT.

Hence, for each kT value measured on site coupled with the cover depth x_d, expected, optimistic and pessimistic values of the corrosion initiation time can be obtained without the need of drilling cores. The method is validated on 111 paired results of kT and x_d, obtained on the emblematic Tokyo's Museum of Western Art.

1. Introduction

Although less conspicuous than chloride-induced corrosion, corrosion damage due to carbonation constitutes a matter of concern. Its incidence may be aggravated in the future by the gradual rise in CO_2 concentration in the air, especially in industrial, motorcar and urban environments, and by the reduction in clinker content in concrete that is taking place in the cement and concrete industry.

The carbonation progress is generally assumed as:

$$x_c = K_c \times t^n \tag{1}$$

x_c is the carbonation depth (mm); K_c is the carbonation coefficient (mm/year^n), t is exposure time/age (year) and n is an exponent, usually taken as 1/2 (the so-called "square-root law").

Hence, applying the "square-root law" (see discussion in Section 2.2), Eq. (1) becomes:

$$x_c = K_c \times \sqrt{t} \tag{2}$$

K_c in Eq. (2) depends on several factors such as the "penetrability" of the concrete cover, the amount of carbonatable material in the matrix, the concentration of CO_2 in the atmosphere, the exposure conditions (temperature, RH, rain, solar exposure), etc.

Eqs. (1) or (2) are often used to estimate the service life of existing concrete structures. Indeed, measurements of the carbonation depth x_c obtained destructively on drilled cores or fragments removed from the surface, at time t_0 allow, by a simple application of Eq. (1) to know K_c and, therefore, to predict the time t at which the carbonation front will reach the steel and depassivate it (when carbonation depth x_c equals cover depth x_d). x_c is typically measured by spraying a pH indicator (usually phenolphthalein) on freshly broken concrete surfaces [1].

This simple approach faces two drawbacks: the destructive or damaging nature of the measurements and the high variability of x_c encountered in old structures. For instance, a range of up to 65 mm in carbonation depths was measured on structures almost 100 years old investigated in Chile [2], which reached a value of 140 mm in a 25 years old bridge investigated in China [3]. The high scatter of x_c results is confirmed by other results presented later (Fig. 1). Hence, to have a representative picture of the x_c values in a structure, a prohibitive number of cores or broken concrete samples is required.

As discussed above, the "penetrability" of the cover concrete is one of the main factors governing the carbonation rate K_c. Air-permeability is one of the most accepted properties to evaluate the "penetrability" of the cover concrete and is one of the easier tests to perform on site. Already in the 90's, a method to estimate the progress of carbonation in concrete, based on intrusive site measurements of air-permeability, was proposed [4]. Non-destructive air-permeability measurements were

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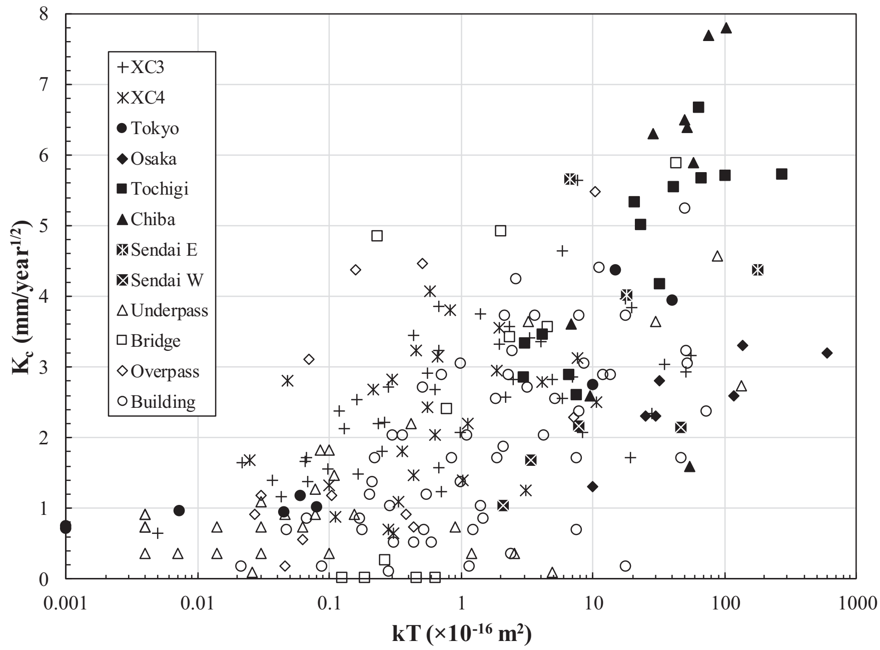

Fig. 1. Relation between K_c and kT for all cases studied.

used to predict the service life of the emblematic Museum of Western Art in Tokyo [5] and of precast concrete segments of the Port of Miami Tunnel [6]. In these two investigations the coefficient of air-permeability kT was measured applying the non-destructive Swiss Standard Method SIA 262/1-E, 2013 [7], described in Section 3.

The purpose of this paper is to present a methodology for assessing the residual service life of reinforced concrete structures at risk of carbonation-induced corrosion, based exclusively on the non-destructive determination of the air-permeability and of the cover depth, both measured on site.

The authors followed a very original and promising approach proposed by Teruzzi [8], who based his investigation on test results of carbonation depth and air-permeability obtained on a single building in the South of Switzerland (Canton Ticino, known for its sunny and mild Mediterranean climate). Teruzzi based his analysis on assessing the carbonation rate K_c on the basis of kT measurements. Data from just one building is not enough to develop a model for general use.

The contribution of this paper is to add robustness to Teruzzi's approach by trying it on a large number of different types of structures, located in Japan, Portugal and Switzerland (North and South), thus covering a wide range of climates and construction and exposure conditions. In addition, the model is extended to the prediction of the corrosion initiation time T_i, in the case where the cover thickness x_d is measured in parallel with kT, with its predictions validated on a real case.

2. Assumptions adopted for the proposed model

2.1. Definition of service life

The corrosion process of steel embedded in concrete is characterized by two well defined stages [9], namely the initiation period (time needed for the carbonation front to reach the position of the affected steel bar, depassivating it) and the propagation period (time needed for the corrosion in the bar to develop sufficiently so as to generate some visible damage). This investigation deals just with the initiation period, which involves a condition that is necessary but not sufficient to have corrosion damage. The propagation period may be very short for surfaces exposed to wetting and drying conditions or very long for surfaces exposed to permanently dry conditions. Therefore, the Service Life predicted by the proposed model is reasonably consistent with the appearance of corrosion symptoms for external surfaces exposed to normal outdoor conditions (e.g. XC4 according to EN 206 [10]). If the elements are located indoors or to extremely dry outdoor conditions, the predicted service life will be too conservative and the corrosion propagation period must be taken into consideration. An approach for empirical estimation of the propagation time for carbonation-induced corrosion, proposed by Torrent and Luco, can be found in [11].

2.2. Rate of carbonation progress

The penetration of CO_2 into concrete can be considered as a purely diffusive process, obeying Fick's 2nd Law, which predicts a carbonation depth proportional to the square root of time (Eq. (2)). The matter is further complicated by the "carbonation" chemical reactions and by the partial and variable blocking effect of moisture in the concrete pores. Most models developed to predict carbonation are based on the "square root" law [12–14], including a coefficient that reduces the predicted carbonation depth for structures exposed to wetting, a fact observed experimentally by Wierig [15].

In the proposed model, the "square-root law" is adopted to convert carbonation depths x_c, measured in old structures, into carbonation rates K_c, applying Eq. (2) (see Fig. 1, later discussed). Consistently, the "square-root law" is also applied to predict carbonation depths, based on the K_c computed with the same "law".

2.3. Age of the structures

The carbonation depths and air-permeability values used to support the model were measured on structures with ages predominantly in the range 10–60 years. Therefore, the proposed model is applicable to structures with ages within the above-mentioned range.