SERVICE LIFE ASSESSMENT OF CONCRETE STRUCTURES BASED ON SITE TESTING

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Abstract

The paper proposes a method, called Exp-Ref, to assess the service life of structures exposed to carbonation-induced corrosion, based on two principles: a) measuring on site, non-destructively, two fundamental durability properties: air-permeability and depth of the cover concrete; b) taking as reference the conditions (given in EN Standards for defined Exposure Classes) leading to an expected service life of 50 years. It is claimed that this approach constitutes a starting point for developing more realistic and robust service life prediction models.

1 INTRODUCTION

Traditionally, Concrete Codes and Standards have applied the "Deemed-to-satisfy" approach [1] to specify durability requirements. Based on the accumulated experience in many countries, a set of primarily prescriptive rules have been established which, when rigorously observed, would result in a service life typically of 50 years (e.g. [2]). Today, many important structures are designed for service lives of 100, 150 or even more years, which clearly exceed the reach of existing experience with reinforced concrete and, therefore, requires some extrapolation via modelling.

Several models have been developed to predict/estimate the service life of reinforced concrete structures, particularly for those under risk of steel corrosion induced by chlorides or carbonation. For carbonation, the most widely used model is Duracrete [3], which assumes a purely diffusive ("Fickian") mechanism of ingress of CO_2; it is taken as reference.

In this paper, the "Exp-Ref" model, already presented for chlorides [4], is developed for the case of carbonation-induced corrosion.

2 THE DURACRETE MODEL FOR CARBONATION

The Duracrete model is based on assuming that the penetration of the carbonation front in concrete can be predicted through Eq. (1):

$$x = \sqrt{2 \cdot C_s \cdot t \cdot D_0 \cdot (t_0 / t)^n \cdot k_c \cdot k_e} \quad (1)$$

$x =$ penetration of carbonation front (mm) after t (years) of exposure
$C_s =$ surface concentration of CO_2 (ppm)
$D_0 =$ coefficient of diffusion of concrete to CO_2 considered/measured at age t_0 (typically 28 days)
$n =$ "ageing exponent", reflecting the rate of decay of the coefficient of diffusion with time, due to hydration beyond age t_0
$k_c =$ curing factor, smaller the longer the moist curing
$k_e =$ environment factor, depending on the exposure condition and cement type

Since Duracrete adopts a semi-probabilistic approach, Eq. (1) is further modified by using "design" values for most variables, involving characteristic values and partial factors.

The time of initiation of corrosion T_i is the time (t) when the carbonation front (x) has reached the outermost reinforcing steel (c). Therefore, from Eq. (1), T_i results:

$$T_i = \frac{c^2}{2 \cdot C_s \cdot D_0 \, (t_0 / T_i)^n \cdot k_c \cdot k_e} \qquad (2)$$

$T_i =$ time of initiation of corrosion (years)
$c =$ cover depth (mm)

The application of (2) has some limitations that make the predictions uncertain and/or subjective, namely:

a) The actual cover depth (c) is taken from the specified value, although it is known that it may differ considerably [5]
b) The coefficient of diffusion (D_0) at age t_0 is established on the basis of accelerated tests made on laboratory specimens, applying non-standard test methods.
c) The surface concentration of CO_2 (C_s) is assumed constant at 5.10^{-4} kg/m³ (258 ppm), stating that it may be "higher for tunnels or other confined spaces"
d) The ageing exponent (n) varies between 0 (for laboratory tests under RH $\leq$65%) and 0.43, depending on the binder type and exposure condition
e) The environmental factor (k_e) is defined only for OPC and OPC+GGBS binders
f) The reduction of D_0 with time (due to further hydration) is a gradual process taking place at the same time when the carbonation front is progressing. Therefore, applying in (2) the full reduction at $t = T_i$ to calculate the penetration of carbonation, overestimates T_i

An important criticism that can be made to this model is that the main materials' characteristics (D_0 and c) are either theoretical ("Theorecrete") or based on laboratory tests ("Labcrete"). The adopted values may deviate significantly from those actually found in the real structure ("Realcrete").

Another weakness of these approaches is that several elusive parameters (C_s, n, k_c, k_e), needed for the prediction, can hardly be measured or established accurately and are, hence, rather arbitrary. As they exert a strong influence on T_i, the estimation of service life is by no means robust and may become subjective and prone to manipulation.

3 CONCEPT OF "REALCRETE" AND "COVERCRETE"

The difference between the "as-built" quality ("Realcrete") and that reflected by the results of laboratory tests conducted on cast specimens, prepared, compacted and cured under almost perfect conditions, i.e. "Labcrete", is well known. The effect on durability of much too frequent bad practices such as: insufficient mixing time, bad compaction (especially in the space between the steel bars and the form), and lack or absence of moist curing (affecting harder the most exposed outer concrete layers) is discussed in [6,7]. In [7], the problem of cover to reinforcement is also addressed, highlighting the negative consequences for durability of too thin or too thick cover depths (cracking).

The concrete cover (“Covercrete”) is the defence barrier of the structural element against the penetration of external aggressive agents. We find, therefore, the unfavourable situation that this defence barrier is the weakest in terms of quality. Moreover, the cast specimens used for laboratory “penetrability” tests are not representative of that of the “Covercrete”. In fact, the only way of knowing the “penetrability” of the vital “Covercrete” is by mean of site tests.

The same applies to the thickness of the cover concrete that protects the steel. The actual cover seldom coincides with the nominal value [5] and is rarely checked on the finished structure, despite the fact that there are electromagnetic and radar covermeters capable of making a sufficiently accurate assessment of its value [8].

4 THE 'EXP-REF' SERVICE LIFE PREDICTION APPROACH

The "Exp-Ref" method for service life prediction for carbonation-induced corrosion of steel, similar as for chlorides [4], consists of three main elements:

- Non-destructive experimental (hence "Exp") assessment of the 'penetrability' and thickness of the "Covercrete" through the application on site of standardized test methods: air-permeability (and concrete moisture check) [9] and covermeters [10]
- Correlation between the measured coefficient of air-permeability and carbonation rate
- Definition of a reference condition (hence "Ref") with a definite service life attributed

4.1 Air-Permeability as Site Durability Indicator.

So far, the only standard method used to specify and control the "penetrability" of the "Covercrete" on site is the "Air-Permeability on the Structure" [9]. This entirely NDT method is capable of measuring the coefficient of air-permeability (kT) on site in up to 6 minutes [11], producing meaningful results if the procedures prescribed in [9] are followed.

4.2 Correlation between air-permeability and natural carbonation rate

Correlations have been established between kT and accelerated carbonation tests [12,13]. In this case, the correlation is based on test results of mostly OPC concretes, the kT values of which were measured at 28 days, and later exposed to natural carbonation in a laboratory-controlled environment, 20°C and 50% RH [15,16] and 60% RH [14]. The carbonation depth was measured at ages of 500 days [15], 2 years [16] and 3.5 years [14].

Fig. 1 presents the results of carbonation rate (CR), expressed as the carbonation depth (x) divided by the square root of exposure time (t), plotted against the coefficient of air-permeability (kT) measured at 28 days. Eq. (3) gives the best correlation (R = 0.89) to the results, with CR in (mm/ $y^{1/2}$) and kT in (10^{-16} m²).

This type of relation has been found also for old structures and used to assess the service life of a Museum in Tokyo [17] and of precast elements for the Port of Miami Tunnel [18].

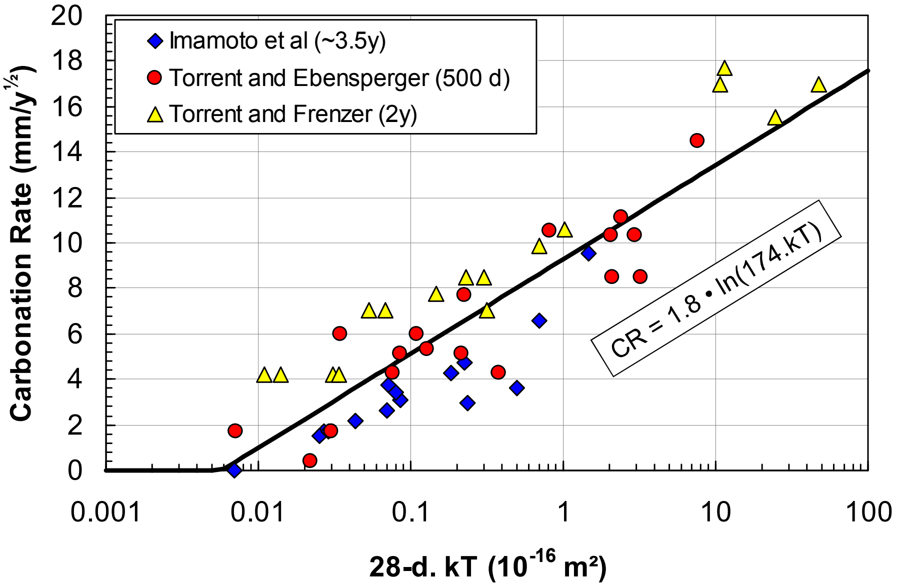

Fig. 1 - Correlation between Carbonation Rate and Coefficient of Air-Permeability kT [14-16]

$$CR = x / \sqrt{t} = 1.8 \cdot \ln(174 \cdot kT) \quad \text{or} \quad CR = 0 \quad \text{if } kT < 1/174 \tag{3}$$

Now, the carbonation rate can be derived from Eq. (1), remembering that, for laboratory tests with RH ≤ 65%, is n = 0 and k_e and k_c (already included in kT) can be assumed as 1.0.

$$CR = x / \sqrt{t} = \sqrt{2 \cdot C'_s \cdot D_0} \tag{4}$$

where C'_s is the CO_2 concentration in the laboratory environment.

Combining (3) and (4) we can write:

$$2 \cdot D_0 = \frac{3.24}{C'_s} \ln^2(174 \cdot kT) \tag{5}$$

Introducing (5) in (2), and eliminating k_c, because the effect of curing is already included in the site measurement of kT, we have for a concrete under a given exposure class:

$$T_i = \frac{C'_s}{C_s} \cdot \frac{c^2}{3.24 \cdot \ln^2(174 \cdot kT) \cdot (t_0 / T_i)^n \cdot k_e} \tag{6}$$

Eq. (6) allows us to calculate the initiation time T_i, now as function of the air-permeability (kT) and the cover depth (c), both measured on the structure. The problem is that the uncertain parameters C_s, n, k_e are still present in the formula.

4.3 Reference Condition

After many years of development, experts from most European countries have agreed on a common classification of exposures [2] covering all the conditions likely to be found in Europe (see Table 1 for a description of carbonation-induced corrosion exposure classes).

Secondly and more important, they agreed that concretes with a w/c ratio below a certain w/c_{max} limit and a cover depth above a certain c_{min} limit [2,19], if well processed according to [20], are expected to reach a service life of 50 years under a defined Exposure Class. These limits are shown in the first two rows of Table 2.

Table 1 - Exposure Classes for carbonation-induced corrosion environments [2]

Class Designation	Description of Environment	Examples
XC1	a - Dry b - Permanently wet	- Inside buildings with low air humidity - Permanently submerged in water
XC2	Wet, rarely dry	Many foundations
XC3	Moderate humidity	Inside buildings w/moderate or high air humidity; external sheltered from rain
XC4	Cyclic wet and dry	Concrete surfaces subject to water contact, not within exposure class XC2

Table 2 - Requirements for 50 years service life [2,19]

	Exposure Classes				
Characteristic	XC1a	XC1b	XC2	XC3	XC4
w/c_{max}	0.65		0.60	0.55	0.50
c_{min} (mm)	15		25		30
w/c_{ref}	0.63		0.58	0.53	0.48
kT_{ref} (10^{-16} m²)	1.41		0.79	0.45	0.25
c_{ref} (mm)	25		35		40
T_p (y)	45	10	10	25	2
T_{iref} (y)	5	40	40	25	48
β (y/mm²)	0.24	1.94	0.79	0.39	0.43

To comply with those limits, the target values of w/c and c (reference values), should have a margin respect to the limiting values: $w/c_{ref} = w/c_{max} - 0.02$ and $c_{ref} = c_{min} + 10$ mm.

A relation between gas-permeability and w/c ratio, proposed in [21] and validated for kT results [4] is adopted:

$$\log kT_{ref}\,(10^{-16}\ \text{m}^2) = -3 + 5 \cdot w/c_{ref} \qquad \text{(Eq. 2.1-107 of [20])} \qquad (7)$$

Therefore, a concrete structure with a cover depth c_{ref} and air-permeability kT_{ref} is expected to have a service life (SL_{ref}) of 50 years, serving as the reference condition (see rows 3-5 in Table 2).

Moreover, we know that:

$$SL = T_i + T_p \qquad (8)$$

SL=	service life (y)
T_i =	initiation period (y)
T_p =	corrosion propagation period (y)

In the case of exposure to chlorides, it is acceptable to assume $T_p = 0$, due to the availability of O_2 and moisture and the low electrical resistivity of the chloride-contaminated concrete [4]. For carbonation, this is not the case, and T_p has to be taken into account in the assessment of service life.

Fig. 2 shows the relative carbonation and carbonation-induced corrosion rates as function of the relative humidity of the environment [22]. The location of the 5 exposure classes is also shown schematically. The need to subdivide class XC1 into XC1a and XC1b is now evident, given the different resulting carbonation and corrosion rates. Based on this qualitative description and the quantitative model proposed in [23], the corrosion propagation time T_p (for cracking onset) can be estimated for each class (see row 6 of Table 2).

The T_{iref} values, for the reference service life SL_{ref} = 50 y, are shown in row 7 of Table 2.

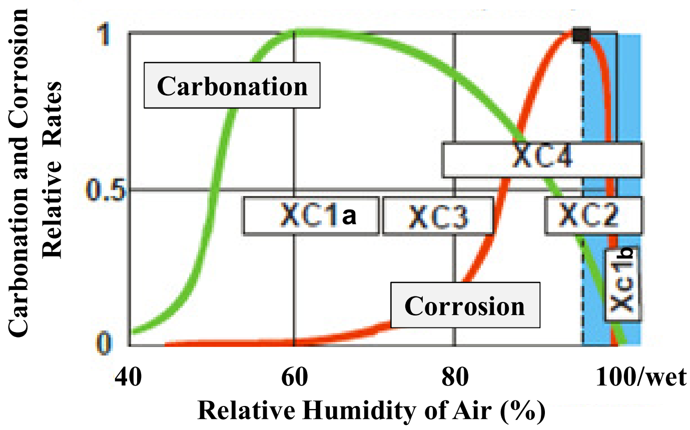

Fig. 2 - Carbonation and corrosion relative rates as function of RH of air [22]

Now, applying Eq. (6) to the reference condition, we have:

$$T_{iref} = \frac{C'_s}{C_s} \bullet \frac{c_{ref}^2}{3.24 \cdot \ln^2(174 \cdot kT_{ref}) \cdot (t_0 / T_{iref})^n \cdot k_e} \tag{9}$$

Dividing (6) by (9) and assuming that C_s and factor k_e are the same for the same exposure class, and that the decay factor $(t_0/T_i)^n$, after so many years of hydration, is also the same for the reference condition and for the investigated case, we can write:

$$T_i = \frac{c^2}{c_{ref}^2} \bullet \frac{\ln^2(174 \cdot kT_{ref})}{\ln^2(174 \cdot kT)} \bullet T_{iref} \tag{10}$$

The service life SL can be computed from Eqs. (11, 12), using the β and T_p values of the corresponding exposure class, indicated in rows 6 and 8 of Table 2.

$$SL = \beta \bullet \frac{c^2}{\ln^2(174 \cdot kT)} + T_p \tag{11}$$

$$\beta = T_{iref} \bullet \ln^2(174 \bullet kT_{ref}) / c_{ref}^2 \quad (12)$$

Eq. (11) provides an estimate of the service life of a concrete structure SL (years), exposed to a given carbonation-induced corrosion class, as function of the measured cover depth c (mm) and the coefficient of air permeability kT (10^{-16} m²), both measured on site. Obviously, the higher the value of c and the lower the value of kT, the longer the service life SL.

A transformation of Eq. (12) allows to estimate the penetration of the carbonation front, as function of the exposure class and the measured value of kT (10^{-16} m²):

$$x = (t / \beta)^{1/2} \bullet \ln(174 \bullet kT) \quad (13)$$

x = carbonation depth (mm)
t = time (y)
β = (y/mm²), value given in row 8 of Table 2 for each exposure class; from (13) the rate of carbonation for a given kT is inversely proportional to $\beta^{1/2}$

For instance, using the values of kT measured on the Port of Miami Tunnel (for assumed classes $XC1_a$/XC3), the carbonation depth with the Exp-Ref method can be estimated, comparing them with the values predicted by other models [18], Table 3. The values predicted by "Exp-Ref" (for classes XC1a/XC3) fit well to the other methods, slightly on the safe side.

Table 3 - Predicted carbonation depth after 150 years for Port of Miami Tunnel

	Predicted Carbonation Depth (mm) @ 150 years after method:			
	Analytical	Based on kT site measurements		
	Duracrete	Parrott	Old Structures	Exp-Ref (XC1a / XC3)
72 h Curing (kT= 0.027)	24	14	38	38 / 30
18 h Curing (kT= 0.057)	35	19	48	57 / 45

5 CONCLUSIONS

The Exp-Ref approach, based on measurements conducted directly on the structure ("Realcrete"), in particular of the air-permeability and thickness of the "Covercrete", has been applied to carbonation-induced corrosion. Since the reference condition, on which the model is based, corresponds to 50 years of service life, the extrapolation is for shorter periods than for a model starting from time zero.

The proposed method has two main advantages over other methods:

a) it is concerned with the quality actually achieved in the as-built structure, including important factors for the durability performance of the structure such as concrete production, placement, compaction, finishing and curing, as well as proper placement and fixing of the steel reinforcement

b) there are no coefficient or factors to be chosen freely by the user, except the definition of the Exposure Class

It is a starting point towards more realistic and robust service life prediction models.

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