Probabilisticservicelifeof RCstructures under carbonation

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The service life of reinforced concrete structures is assessed for carbonation environments using mathematical models based on different tests: carbonation test-based modelling and air permeability test-based modelling. The study includes experimental testing of five concrete mixes with respect to compressive strength, accelerated carbonation and air permeability with different types of cement, in order to assess the models using probabilistic calculus. Both mathematical models are part of the Portuguese National Annex to the European standard EN 206 for the estimation of design service life. Engineers have the option of choosing which of the two models to use, which means that using either model should produce similar results. The design service life results show that the two models do not converge. The different principle of each test – accelerated carbonation and air permeability – and their different characteristics regarding the various parameters of the modelling equations are some of the aspects discussed.

Notation

a	constant value taken as 150
b	calcium oxide amount in the hydrated cement matrix of the concrete, (kg/m^3)
C_{accel}	carbon dioxide concentration of 90 × 10^{-3} kg/m^3
c	concrete cover (m)
f_c	concrete compressive strength (MPa)
f_{td}	concrete tensile strength (MPa)
$g(x)$	limit state function
i_{corr}	corrosion rate
KT	coefficient of air permeability (m^2)
k_a	testing diffusion accelerated carbonation (m/year)
k_0	constant value that takes into account the testing method and conditions of LNEC E391 (LNEC, 1993a)
k_1	parameter that considers the presence of relative humidity (LNEC E465 (LNEC, 2009b))
k_2	parameter that quantifies the curing influence (LNEC E465 (LNEC, 2009b))
m	parameter that depends on the relative humidity of the concrete and on the exposure class
n	parameter that quantifies the wet/dry cycle influence in time (LNEC E46 (LNEC, 2009b))
P_f	probability of failure
p	parameter that depends on the relative humidity of the concrete and on the exposure class
R_{C65}	accelerated carbonation resistance (kg/m^3)/(m^2/year)
t	time (years)
t_i	initiation period (years)
t_L	design service life (years)
t_p	propagation period (years)
t_0	reference period = 1 year
t_1	testing duration of accelerated carbonation (years)
X_1	testing carbonation depth due to accelerated carbonation (m)
x	carbonation depth (m)
y	relative reduction of the steel reinforcement radius ( ) %
α	coefficient that takes into account the type of corrosion (α = 2 due to carbonation, α = 10 for chlorides pitting corrosion)
ΔC	difference of carbon dioxide concentration between the exterior and the carbonation front (kg/m^3)
λ	model uncertainty
φ_0	initial diameter of the ordinary reinforcement bar (m)

Introduction

Several prediction models for concrete structures exposed to carbonation have been proposed in the past decades, as pre- sented by Sanjuán *et al*. (2003). More recently, various models for carbonation and chloride contamination have been pro- posed by other researchers, international research projects and standards (Boutz *et al*., 2008; CS, 2004; DuraCrete, 2000; EHE, 2008; Kamaitis, 2008; Kwon *et al*., 2009; Lay *et al*., 2003; Life-365, 2012; NIST, 2011; SCA, 2007; Silva *et al*., 2014; Taffes and Sistonen, 2013). Nevertheless, these models present some limitations such as reliable information regarding the statistical dispersion of variables. Additionally, there is difficulty in implementing some of these models alongside time-consuming procedures (Silva *et al*., 2014; Taffes and Sistonen, 2013).

A performance-based approach has been introduced by the Portuguese specification LNEC E465 (LNEC, 2009b), where a required performance is maintained throughout the intended life of the structure, along with the optimisation of the service life costs (Narasimhan and Chew, 2009). This approach is ana- logous to those already in use in other European countries such as Finland, Sweden (SCA, 2007) and Spain (EHE08 (EHE, 2008)).

In the case of the performance-based Portuguese specification (LNEC E465 (LNEC, 2009b)), which follows the philosophy of benchmark recommendations and standards (DuraCrete (2000), fib bulletin 34 (fib, 2006) and ISO 16204 (ISO, 2012)) two different mathematical models are presented as described below.

(a) Modelling equations based on carbon dioxide diffusion tests through the concrete (LNEC E391 (LNEC, 1993a)). The first Fick's law is used assuming the carbon dioxide flow as stationary. The carbonation depth is a function of time and the carbon dioxide coefficient of diffusion.
(b) Modelling equations based on air permeability tests in the concrete (LNEC E392 (LNEC, 1993b)). This model represents the co-relation between the values of the coefficient of air diffusion and the coefficient of air permeability in the concrete. In this case, the carbonation depth is a function of time and the coefficient of air permeability of the concrete cover.

The first model has already been employed and analysed by Marques and Costa (2010), Marques *et al*. (2013) and Neves *et al*. (2012b) for tested concrete compositions for carbonation.

As regards the second model, based on air permeability tests, the current study is the first to present the comparison with the carbonation-based model using a probabilistic method for both models. The relationship between carbonation depth and air permeability has been assessed by different authors (Neves *et al*., 2012a; Nilsson and Luping, 1995).

Reinforcing steel corrosion in carbonation environments

The main factors that cause steel reinforcement to corrode are: the surrounding environment (Bakker, 1988; Verbeck, 1958); the quality of the materials (concrete and steel); and the quality of the construction works (compaction and curing) which affect directly the concrete porosity (Neves *et al*., 2012b).

Tuutti (1982) presented a model that considers the effect of deterioration by corrosion divided into two phases: the initiation phase (initiation period t_i), where the aggressive agent penetrates into the concrete until it reaches the reinfor- cing steel, in the case of carbon dioxide diffusion, until the car- bonation depth is equal to the thickness of the concrete cover; and the propagation phase (propagation period t_p), which begins with the onset of corrosion and where the duration depends on the limit established as regards a chosen criterion: cracking, delamination or steel section loss. The sum of both phases corresponds to the design service life of a structure – $t_L = t_i + t_p$.

European standard EN 206-1 (CEN, 2000c) and Eurocode 2 (EN 1992-1-1 (CEN, 2004)) separate the environments in terms of the aggressive agents, and both documents present exposure sub-classes for different microenvironments. In the case of carbonation-induced corrosion, there are four classes

- XC1 – concrete inside buildings with low air humidity or concrete permanently submerged in water
- XC2 – concrete surfaces subject to long-term water contact; this includes many foundations
- XC3 – concrete inside buildings with moderate or high air humidity or external concrete sheltered from rain
- XC4 – concrete surfaces subjected to water contact or high humidity on a cyclic basis.

In this paper, exposure classes XC3 and XC4 are the ones included in the modelling analysis owing to their higher level of aggressiveness.

Service life modelling

Initiation period t_i based on accelerated carbonation tests

The concept of carbonation resistance R_{C65} expressed by per- formance-based specification (LNEC E465 (LNEC, 2009b)), corresponds to the ratio between the amount of carbon dioxide necessary for complete carbonation of a concrete unit volume and the coefficient of diffusion through the concrete in equilibrium with an environment of 65% relative humidity (RH) and a temperature of 20°C.

The carbonation resistance R_{C65} (Equation 1) results from the laboratory results through an accelerated process with a con- centration of carbon dioxide C_{accel} of 90×10^{-3} kg/m^3 (LNEC E391 (LNEC, 1993a)). The duration of testing is t_1 and the subsequent carbonation depth is X_1

$$1: \quad R_{C65} = \frac{2C_{accel}t_1}{X_1^2} = \frac{2C_{accel}}{k_a^2}$$

The performance-based specification (LNEC E465 (LNEC, 2009b)) adopted from CEB (1997) includes the equation that expresses the carbon dioxide diffusivity of hardened concrete throughout time – carbonation depth x, according to Equation 2

$$2: \quad x = \sqrt{\frac{2 \times \Delta C}{R_{C65}} t}\sqrt{k_0 k_1 k_2}\left(\frac{t_0}{t}\right)^n$$

where $\Delta C = 0.7 \times 10^{-3}$ kg/m^3 is the difference in the carbon dioxide concentration between the exterior and the carbona- tion front; k_0 equals 3 and is a constant value that takes into account the testing method and conditions (LNEC E391 (LNEC, 1993a)); k_1 considers the presence of relative humidity (LNEC E465 (LNEC, 2009b)); k_2 quantifies the curing influ- ence: 1·0 for normalised cure and 0·25 for a 3 d period of curing (LNEC E465 (LNEC, 2009b)); t_0 is the reference period = 1 year; and n is the parameter that quantifies the wet/dry cycle influence in time (LNEC E465 (LNEC, 2009b)). Table 1 shows the values of parameters k_1 and n for all exposure classes.

The initiation period t_i is expressed as follows

3: $$t_i = \left[\frac{R_{C65}c^2}{1.4 \times 10^{-3} k_0 k_1 k_2 t_0^{2n}}\right]^{1/(1-2n)}$$

Initiation period t_i based on air permeability tests

The model for the calculus of the initiation period t_i based on air permeability tests is proposed as a direct alternative to the one presented in the previous section.

Following LNEC E465 (LNEC, 2009b), this second model results from the fact that it has been experimentally observed that there is a close relation between air diffusion and air per- meability, where the pressure gradient is the driving force.

Following this principle, Equation 4 was written to calculate the carbonation depth

4: $$x = \left[\frac{a^{2.5} t^{2.5p} m \mathrm{KT} \times 10^{16}}{b^{1.25}} k_2\right]^{1/2.5}$$

where x is the carbonation depth (mm) at time t (years); m and p are parameters that depend on the relative humidity of the concrete and consequently on the exposure class (Table 2). The parameter b (kg/m^3) is the calcium oxide of the hydrated cement matrix of the concrete, which depends on the type of binder used and on the exposure class. The parameter a is a constant value, taken as $a = 150$, which accounts for the adjust- ment of the equation in relation to the test. The variable KT is the coefficient of air permeability of the concrete cover in

Table 1. Values of k_1 factor and n factor (LNEC E465 (LNEC, 2009b))

	XC1	XC2	XC3	XC4
k_1	1	0·2	0·77	0·41
n	0	0·183	0·02	0·085

Table 2. Values of m, p and b factor (LNEC E465 (LNEC, 2009b))

			b: kg/m^3		
RH: %	m[a]	p	CEM I[b]	CEM II/B	CEM IV
70 (XC3)	0·725	0·48	460	350	230
80 (XC4)	0·347	0·42	485	360	240

[a]Tests were conducted on specimens in equilibrium with RH=65% instead of RH=60%. The values of m were changed proportionally
[b]Also applicable to CEM II/A-L

exposure humidity conditions; it depends on m and therefore on the exposure class.

The equation in terms of t_i is expressed as follows

5: $$t_i = \left[\frac{b^{0.5}c}{\left(a\, m \mathrm{KT} \times 10^{16}\right)^{0.4}}\right]^{1/p}$$

where c is the concrete cover (mm), which corresponds to the limit of the carbonation depth immediately before the end of the initiation period.

Propagation period t_p – corrosion modelling

The propagation period corresponds to the beginning of cor- rosion of the steel reinforcement until a certain level of deterio- ration is reached, which can result in crack formation due to the steel's increase of volume, delamination of concrete cover or rupture of the steel bars due to loss of section.

The modelling of the propagation period is based on quantifi- cation of the corrosion rate of the steel reinforcement and the tension strength of the concrete cover.

Specification LNEC E465 (LNEC, 2009b) defines the minimum values of t_p, based on Faraday's law and empirical equations shown as follows

6: $$t_p = \frac{y\varphi_0}{1.15\alpha i_{corr}}$$

where i_{corr} (μA/cm^2) is the corrosion rate (Table 3); φ_0 (mm) is the initial diameter of the ordinary reinforcement bar; α is the

Table 3. Corrosion rate i_{corr} against corrosion levels and exposure classes XC (LNEC E465 (LNEC,2009b))

Corrosion rate, i_{corr}: μA/cm^2	Corrosion levels	Exposure classes
<0·1	Negligible	XC1/XC3
0·1–0·5	Low	XC2/XC4
0·5–1	Moderate	XC4
>1	High	—

coefficient that takes into account the type of corrosion (α = 2 due to carbonation, α = 10 for chloride pitting corrosion); and y (%) is the relative reduction of the steel reinforcement radius obtained as follows

$$7: \quad y = \left[74.5 + 7.3\,\frac{c}{\phi_0} - 17.4 f_{td}\right]\frac{0.2}{\phi_0}$$

where f_{td} (MPa) is the concrete tensile strength (obtained from the Brazilian test) and c (mm) is the concrete cover depth.

Probabilistic method

In Eurocode 0 (EN 1990 (CEN, 2002)) three reliability classes are defined – RC1, RC2 and RC3 – relating to the importance of a certain structure/construction considered in terms of consequences due to failure. Each class is represented by a maximum probability of failure P_f, which takes into account the statistical dispersion in action effects, the uncertainties in resistances and the uncertainties of the chosen model. The corrosion effect in reinforced concrete (RC) structures varies widely and therefore the performance-based approach defined in LNEC E465 (LNEC, 2009b) considers the serviceability limit states as in Table 4.

The probabilistic analysis of lifetime distribution is carried out using Equations 8a and 8b with the statistical parameters of the involved variables (mean and standard deviation). The mean values of each variable are based on the experimental programme and LNEC E465 (LNEC, 2009b), whereas the values adopted for the standard deviation are based on fib (2006) and Val and Trapper (2008).

The implementation of the probabilistic calculus for the design lifetime has been carried out by means of the Monte Carlo method. The random variables of the limit state function have been considered with their probability distribution according to reference documents (Ferreira, 2004; fib, 2010; Lindvall, 2003).

Equations 8a and 8b express the limit state functions used for the calculus of the design service life t_L for carbonation- based and permeability-based testing, respectively. In both equations, t_g represents the intended target life depending on the type of structure. The model uncertainty is represented by λ

$$8a: \quad g(x) = t_L - t_g = \lambda\left\{\left[\frac{R\,c^2}{1.4\times 10^{-3}\,C_S\,k_0 k_1 k_2 t_0^{2n}}\right]^{1/(1-2n)} + \frac{y\phi_0}{1.15\times\alpha i_{corr}}\right\} - t_g$$

$$8b: \quad g(x) = t_L - t_g = \lambda\left\{\left(\frac{b^{1.25}c^{2.5}}{a^{2.5}m\,KT\times 10^{16}}\right)^{1/(2.5p)} + \frac{y\varphi_0}{1.15\alpha i_{corr}}\right\} - t_g$$

The probability of failure may be expressed as the probability for which the limit state function is negative (Equation 9)

$$9: \quad P_f = P[g(x) < 0]$$

Experimental programme

Even though the present study deals with the performance- based method for the estimate of design service life t_L, the definition of the concrete mixes was defined having a prescrip- tive specification (LNEC E464 (LNEC, 2009a)) as reference.

The performance of these compositions was analysed regard- ing the testing results, as to: compressive strength (NP EN 12390-3 (CEN, 2000a); accelerated carbonation depth (LNEC E391 (LNEC, 1993a)); and air permeability (LNEC E392 (LNEC, 1993b)).

Concrete mixes

Considering exposure classes XC3 and XC4, the concrete mixes were made so as to respect the limits of the specification LNEC E464 (LNEC, 2009a) in relation to water/cement (w/c) ratio, cement dosage and cement type.

For each concrete mix, the cements used comply with the European standard EN 197-1 (CEN, 2000b). Table 5 shows

Table 4. Maximum values of P_f – Eurocode 0 (CEN, 2002) and LNEC E465 (LNEC, 2009b)

Reliability classes	Ultimate limit state		Serviceability limit state	
	Eurocode 0 (CEN, 2002): %	LNEC E465 (LNEC, 2009b)	Eurocode 0 (CEN,2002): %	LNEC E465 (LNEC, 2009b): %
RC3	0·001	—	—	2·3
RC2	0·007	—	6·7	6·7
RC1	0·048	—	—	11·5

Table 5. Cements and properties

Cement type	Constituents	Ignition loss: %	Insoluble residue: %	Blaine: cm^2/g	Comp. strength 28 d: MPa
CEM I 52·5R	>95% K	2·2	1·5	4777	61·9
CEM I 42·5R	>95% K	3·0	0·7	3900	58·6
CEM II/A-L 42·5R	>89% K 6% LF	8·1	1·4	3946	53·3
CEM II/B-L 32·5N	>73% K 22% LF	12·8	2·4	4152	39·7
CEMIV/AV32·5R	>69% K 26% FA	2·3	26·3	4292	44·3

Note: K, clinker; LF, limestone filler; FA, fly ash

the cement types and corresponding specific surface (Blaine test), whereas Table 6 presents the constituents of each compo- sition designated according to the cement type.

Tests procedures and results

Prior to the planned tests – accelerated carbonation and air permeability – specimens of all concrete mixes were subjected to specific conditioning in accordance with related standards and laboratory procedures. For each concrete mix, 18 speci- mens were produced.

For the compressive strength tests, samples were cubes with 150 mm side length, and the test itself was carried out accord- ing to the definitions of NP EN 12390-3 (CEN, 2000a). The samples were subjected to wet curing of 100% of relative humidity (RH) until the age of 28 d.

With regard to accelerated carbonation tests, the conditioning comprised a wet curing (RH = 100% at 20 ± 2°C) of 14 d after the mixing of the specimens, followed by a period of 14 d of dry curing in an environment of 50 ± 5% of relative humidity and 20 ± 2°C. At the age of 28 d, all the specimens were intro- duced to the carbonation chamber. The specimens were 100 mm in diameter and 50 mm thick following the criteria of LNEC E391 ((LNEC, 1993a)). After 28 d of conditioning, all the specimens were placed in the carbonation chamber at 20°C and 65% RH and a carbon dioxide concentration of 5%. For each concrete mix, four sets of specimens were produced so that each set could be tested at different ages. Accordingly, the four sets of specimens were removed from the chamber 7, 14, 28 and 43 d after being subjected to accelerated carbonation and then broken into two halves and tested with a solution of 0·5% of phenolphthalein in alcohol (Figure 1).

The specimens prepared for the air permeability tests (Figure 2) were concrete discs with a diameter of 150 mm and 50 mm thick, following the criteria of LNEC E392 ((LNEC, 1993b)) using the Torrent permeability tester (Proceq). The conditioning of the specimens also included a wet curing period of 14 d at 100% RH and 20 ± 2°C with the following 14 d at 65 ± 5%RH and 20 ± 2°C.

The results of the tests are presented in Figures 2 and 4 and Table 7, with mean values and corresponding coefficients of variation.

As regards the accelerated carbonation tests, the results are presented in terms of the coefficient of carbonation k_a (slope of carbonation depth against square of time in mm/√year) and carbonation resistance R_{C65} (Equation 1 in $(kg/m^3)/(m^2/year)$).

As for the air permeability tests, the results are presented in terms of the coefficient of air permeability KT.

Design service life results and discussion

Input data – random and deterministic variables

The calculation of the design service life t_L was carried out considering the required probability of failure (Table 4), based on the limit state functions of Equation 8a for carbonation- based modelling and Equation 8b for permeability-based

Table 6. Composition of the concrete mixes

Concrete mix	Cement dosage	Sand 0·25–0·5	Sand 0·5–1·0	Gravel 8–12	Water	*w/c*
CEM I 52·5R	320	205	657	780	170	0·53
CEM I 42·5R	320	205	657	780	170	0·53
CEM II/A-L 42·5R	320	205	657	780	170	0·53
CEM II/B-L 32·5N	320	210	671	796	154	0·48
CEM IV/A-V 32·5R	320	210	671	796	154	0·48

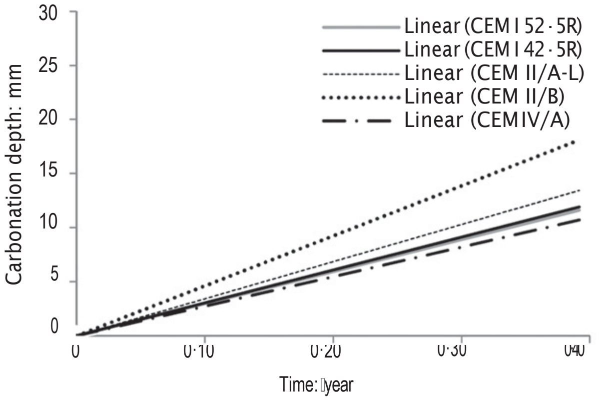

Figure 1. Results of the accelerated carbonation tests

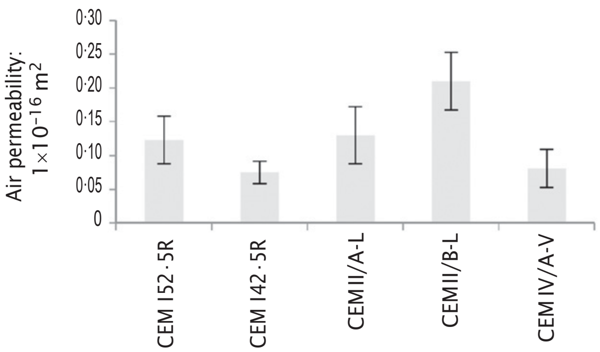

Figure 2. Results of the air permeability (KT) tests

modelling, and Equation 9 for the calculus of the probability of failure for which the limit state function was negative.

The numerical simulation was undertaken using the Monte Carlo method with 100 000 numbers generated for each random variable in accordance with their distribution law and corresponding statistical parameters (Tables 8–11). The option as to whether the variables should be considered as random or deterministic was based on: (*a*) the updated knowledge of their nature along with their distribution laws (Duracrete, 2000; fib, 2006); (*b*) if they were calibrating parameters, usually deterministic; or (*c*) if based on sensitivity analysis it is not rel- evant if the variables are set as random or deterministic (Ferreira, 2004; Marques, 2007).

Modelling results: accelerated carbonation against air permeability

The modelling results of the design service life t_L are presented in Figures 3 and 4. In Figure 3, an example of the perform- ance of the five tested concrete compositions is shown for exposure class XC3, for both mathematical models that are based on the equations and tests regarding accelerated carbo- nation and air permeability tests, respectively. It can be seen that the design service life based on air permeability testing and modelling presents significantly higher values when com- pared with the carbonation-based testing and modelling. Based on these results, the two modelling approaches do not converge. Furthermore, it is also evident that the difference in the performance between each concrete composition is greater for the air permeability modelling results compared with the carbonation-based modelling results.

The modelling results of the design service life t_L of both models are closer to each other for exposure class XC3. The reason for this has to do with the fact that in class XC3 the propagation period t_p, whose modelling or definition does not depend on the accelerated carbonation and air permeability tests, has a higher proportion of the entire calculated service life – t_p = 53 years in class XC3. Comparatively, for class XC4 the contribution of t_p is almost negligible for t_L (t_p = 8 years).

Consequently, poor convergence between carbonation-based modelling and air permeability-based modelling is also observed for class XC3, considering the results of the initiation period, where the influence of the tests on the modelling equations is effective.

Taking into account the two parts of the presented study – (*a*) the experimental work and (*b*) the calculus and analysis of the design service life – it is reasonable to state that, according to both sets of results, those of the laboratory tests and those from the modelling calculus, the two mathematical models do not produce similar results in most cases.

Table 7. Concrete experimental characterisation. Tests results at the age of 28 d – mean values (coefficient of variation (CoV) for R_{C65} and KT)

Concrete mix	f_c: MPa	k_a: mm/√year	R_{C65}: kg year/m^5	KT: 10^{-16} m^2
CEM I 52·5R	62·1	29·5	207 (17%)	0·123 (29%)
CEM I 42·5R	56·1	32·1	175 (18%)	0·075 (22%)
CEM II/A-L 42·5R	47·5	33·3	162 (14%)	0·130 (32%)
CEM II/B-L 32·5N	41·1	46·2	85 (9%)	0·210 (20%)
CEM IV/A-V 32·5R	62·3	25·6	274 (16%)	0·081 (35%)

Note: f_c, compressive strength (CoV varied between 2% and 5%); k_a, carbonation coefficient; R_{C65}, carbonation resistance; KT, coefficient of air permeability

Table 8. Carbonation-based modelling class XC3 – distribution laws of the variables and corresponding statistical parameters

Variables	Mean: μ	Standard deviation: σ	Distribution law
Initiation			
Cover, c (c_{nom})	35 mm	8 mm	Log-normal
Carbonation resistance, R_{C65}	(Table 7)	(Table 7)	Normal
Test parameter, k_0	3	—	Deterministic
Rel. humidity parameter, k_1	0·77	—	Deterministic
Curing parameter, k_2	1	—	Deterministic
Wet/dry cycle parameter, n	0·02	—	Deterministic
Propagation			
Corrosion current density, i_{corr}	0·10 μA/cm^2	0·20 μ	Normal Normal
Tensile strength, f_{td}	2MPa	0·20 μ	Deterministic
Steel bar diameter, φ_0	8mm	—	

Table 9. Carbonation-based modelling class XC4 – distribution laws of the variables and corresponding statistical parameters

Variables	Mean: μ	Standard deviation: σ	Distribution law
Initiation			
Cover, c (c_{nom})	40 mm	8 mm	Log-normal
Carbonation resistance, R_{C65}	(Table 7)	(Table 7)	Normal
Test parameter, k_0	3	—	Deterministic
Rel. humidity parameter, k_1	0·41	—	Deterministic
Curing parameter, k_2	1	—	Deterministic
Wet/dry cycle parameter, n	0·085	—	Deterministic
Propagation			
Corrosion current density, i_{corr}	0·10 μA/cm^2	0·20 μ	Normal Normal
Tensile strength, f_{td}	2MPa	0·20 μ	Deterministic
Steel bar diameter, φ_0	8mm	—	

Table 10. Permeability-based modelling class XC3 – distribution laws of the variables and corresponding statistical parameters

Variables	Mean: μ	Standard deviation: σ	Distribution law
Initiation			
Cover, c (c_{nom})	35 mm	8 mm	Log-normal
Air permeability, KT	(Table 7)	(Table 7)	Normal
Test parameter, a	150	—	Deterministic
Calcium oxide of cement matrix, b	(Table 2)	—	Deterministic
Test RH parameter, m	0·725	—	Deterministic
Concrete RH parameter, p	0·48	—	Deterministic
Propagation			
Corrosion current density, i_{corr}	0·10 μA/cm^2	0·20 μ	Normal Normal
Tensile strength, f_{td}	2MPa	0·20 μ	Deterministic
Steel bar diameter, φ_0	8mm	—	

This is due to the three main differences between the two models, as described below.

(a) Different equations and therefore different uncertainty levels.
(b) Different tests – the nature of the carbonation test involves both physical and chemical processes. In the air permeability test, the property assessed is of a physical nature. However, the modelling equation includes the parameter b, which takes into account the type of binder used in the concrete composition. The binder reflects the chemical effect on the concrete performance quantifying the dosage of calcium oxide of the hydrated cement differently. The accuracy of the modelling of this effect requires extensive further discussion, which is beyond the scope of this paper.
(c) The dispersion of the results of the air permeability test is approximately double those of the accelerated carbonated tests (Table 6). Even though the experimental results of the present work may not be sufficient to be representative of such a difference concerning the dispersion of the testing results, other research studies

Table 11. Permeability-based modelling class XC4 – distribution laws of the variables and corresponding statistical parameters

Variables	Mean: μ	Standard deviation: σ	Distribution law
Initiation			
Cover, c (c_{nom})	40 mm	8 mm	Log-normal
Air permeability, KT	(Table 7)	(Table 7)	Normal
Test parameter, a	150	—	Deterministic
Calcium oxide of cement matrix, b	(Table 2)	—	Deterministic
Test RH parameter, m	0·347	—	Deterministic
Concrete RH parameter, p	0·42	—	Deterministic
Propagation			
Corrosion current density, i_{corr}	0·50 μA/cm^2	0·20μ	Normal
Tensile strength, f_{td}	2 MPa	0·20μ	Normal
Steel bar diameter, ϕ_0	8 mm	—	Deterministic

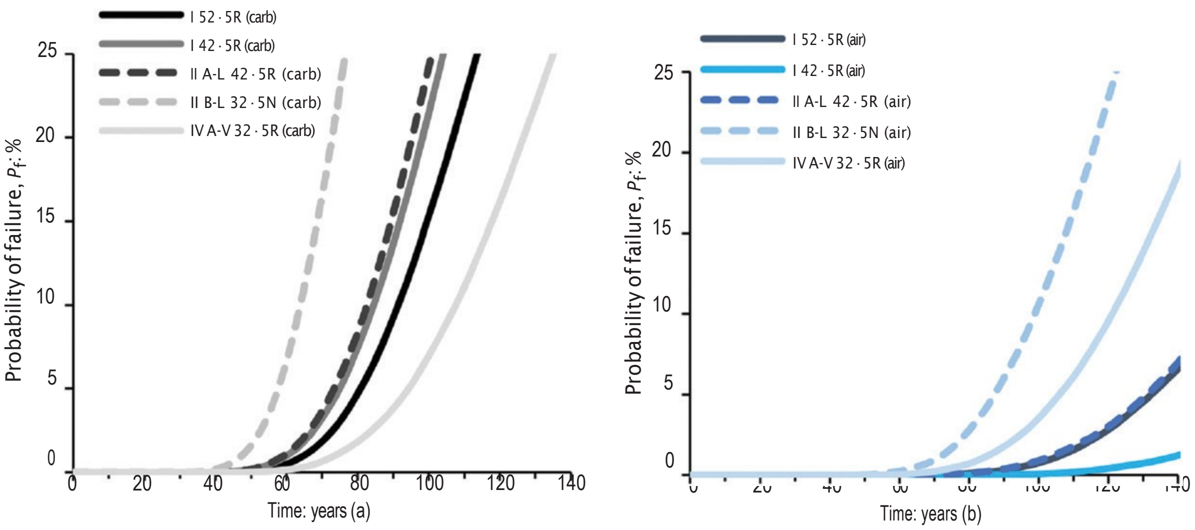

Figure 3. Performance of concrete compositions with time – exposure class XC3: (a) carbonation modelling – XC3; (b) air permeability modelling – XC3

have observed a similar problem despite larger sampling of results (Neves *et al*., 2012a; Nilsson and Luping, 1995).

Exposure classes XC3 and XC4 were chosen to be analysed in this study, as these represent environments where the onset of corrosion in RC structures is more likely to take place. The five chosen concrete mixes include types of cement that present higher commercial demand in certain countries in southern Europe. Considering the overall analysis, some results may, however, be considered 'unrealistic', as it seems inaccurate to conclude that any RC structure, without significant retrofitting intervention, will last more than 100–120 years.

Considering that none of the models can be considered as the 'accurate' one, in order to analyse to what extent the dispersion of the testing results is actually affecting the convergence between both models, further analysis should be undertaken regarding either the calibrating parameters or the statistical parameters of the experimental data.

To recommend a possible variation in the modelling equations of the service life prediction to bring the results of both modelling equations closer together, in this study it was chosen to 'consider' the carbonation-based mathematical model as the 'accurate' modelling and thus to assess which changes could be made to the air permeability-based model (see following section).

Air permeability modelling: sensitivity analysis and recommended modelling variations

Initiation period against each modelling variable

With regard to the diffusion of agents such as carbon dioxide, the equations that model the concrete performance include

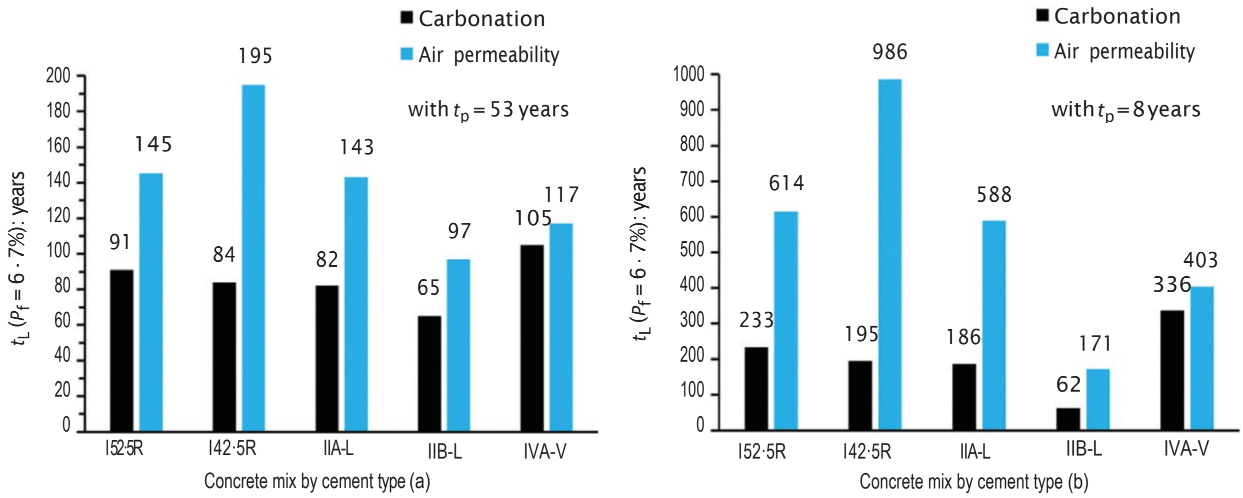

Figure 4. Design service life t_L of tested concrete compositions for exposure classes (a) XC3 and (b) XC4

different variables. These variables represent phenomena that altogether simulate interaction between the external agent – carbon dioxide – and the resistance to its penetration into concrete. The importance of each variable is different, and the corresponding weight can be observed from Equation 5.

This section presents a sensitivity analysis with the quantifi- cation of the influence of each variable on the initiation period t_i for the air permeability modelling. The procedure for a specific variable involved the setting of an interval of values within known practical limits, the fixing of the remaining vari- ables and subsequently the calculus of t_i for each value. The results are presented in Figure 5, where the variation of each variable is shown in relation to the variation of the initiation period t_i.

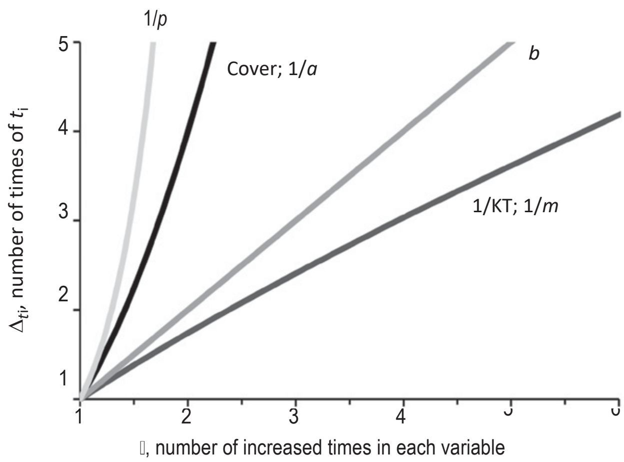

Figure 5. Sensitivity of t_i to each variable modification

From Figure 5 it can be seen that the variable with the highest influence on the initiation period is the parameter p, followed by the concrete cover, c, and the parameter a, all having expo- nential relationships with t_i. Parameter b, relating to the type of cement, is directly and linearly proportional to the initiation period. The air permeability KT and the parameter m are the variables with the least weight on the variation of time, where an increase of 2·5 times for these variables is required to increase the initiation period by 2 times.

Influence of parameter *a*

According to the previous subsection, it is observed that, mathematically, the variables that most affect the initiation period t_i using air permeability modelling are the parameter p, the concrete cover, c, and the parameter a. Given this, and the fact that the latter is a calibration parameter used to adjust the empirical side of the equation, in this section parameter a is changed to assess its impact on the modelling results of the air permeability initiation period t_i and the results are then com- pared with the carbonation modelling results.

The original definition of parameter a in LNEC E465 (LNEC, 2009b) is set to a = 150. Figures 6 and 7 show, for exposure classes XC3 and XC4, respectively, the modelling results of the carbonation-based modelling alongside the curves for the air permeability modelling considering a = 150, a = 225 and a = 300. For concrete compositions with cement I and II and both exposure classes, the estimated performance curves using the air permeability-based modelling and parameter a between 225 and 300 present results closer to the carbonation-based modelling. For the composition with cement type IV A-V, apparently, the curves closest to the carbonation modelling are

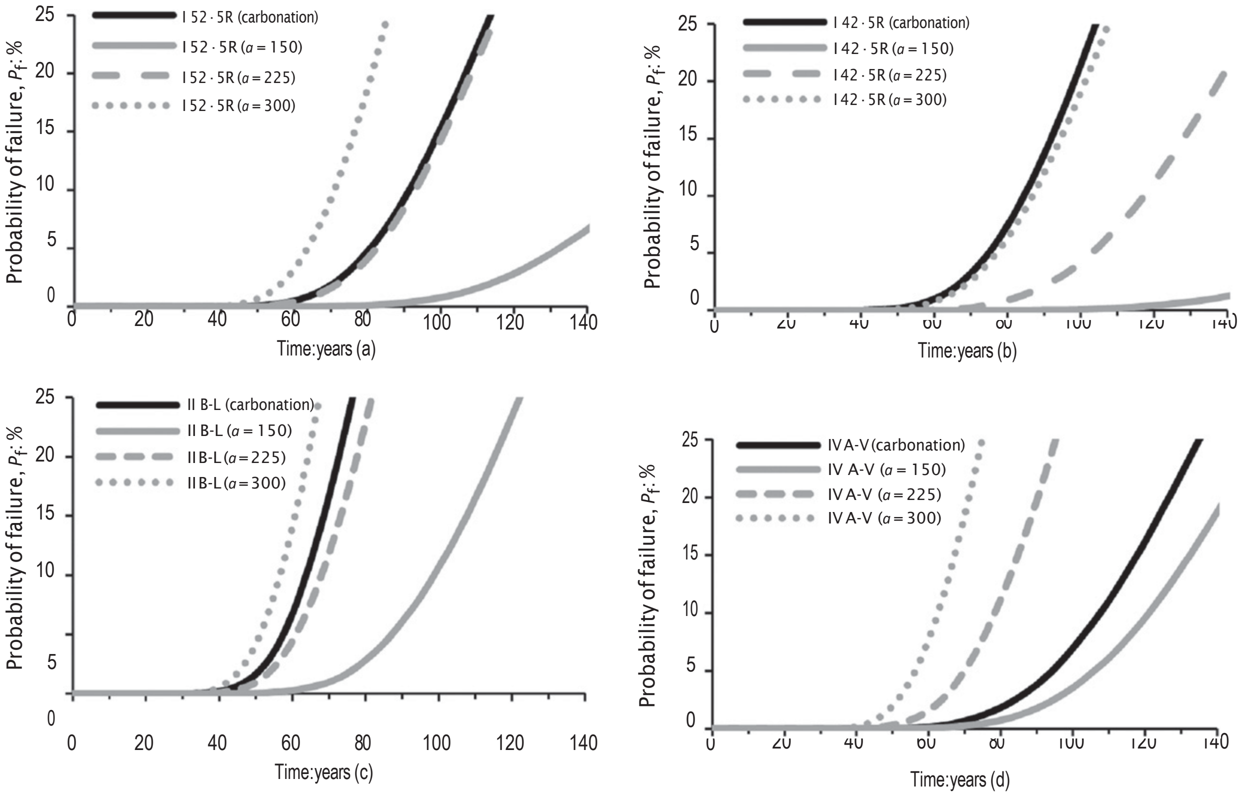

Figure 6. Performance of concrete compositions through time. Carbonation modelling compared with air permeability modelling with variation of parameter *a* – class XC3: (a) CEM I 52·5R; (b) CEM I 42·5R; (c) CEM II/B-L 32·5N; (d) CEM IV/A-V 32·5R

those using parameter *a* = 150, namely, the original value set by LNEC E465 (LNEC, 2009b).

Accordingly, considering the assumption stated above, chan- ging the parameter *a* alone to higher values between 225 and 300 can bring closer together the results of the modelling using both approaches – carbonation-based and air permeability- based. In this study, the exception to this tendency seems to be the concrete composition with cement type IV A-V, for which parameter *a* = 150 provides air permeability modelling results closer to carbonation-based modelling results. However, as mentioned before, the air permeability equations simulate the carbonation effect through the physical effect of permeability and then the chemical effect through the quantification of the available dosage of calcium oxide of the hydrated cement. This dosage, to be used in the modelling equations, is set by the specification LNEC E465 (LNEC, 2009b) assuming that, com- bined with the air permeability test, this definition represents the complete effect of carbonation diffusion. Regarding air permeability modelling for carbonation diffusion in concrete, it is the understanding of the present authors that the difference in the available dosage of calcium oxide of the hydrated cement for different types of cements should be carefully addressed and further discussed in future studies.

Conclusions

Modelling procedures based on accelerated carbonation and air permeability tests are set to be an alternative to each other using a probabilistic approach, which means that the design service life calculated using both models should be similar.

With regard to carbonation-induced corrosion, overall the modelling results show that the two methods do not present similar results. This difference is likely to be related to the nature of the tests, where the carbonation test involves both physical and chemical processes, whereas in the air per- meability test, the property directly assessed is of a physical nature, wherein the chemical effect is modelled mathematically through parameter *b*, which is the available dosage of calcium oxide of the hydrated cement.

This study shows the importance of further discussion for the improvement of the convergence between carbonation

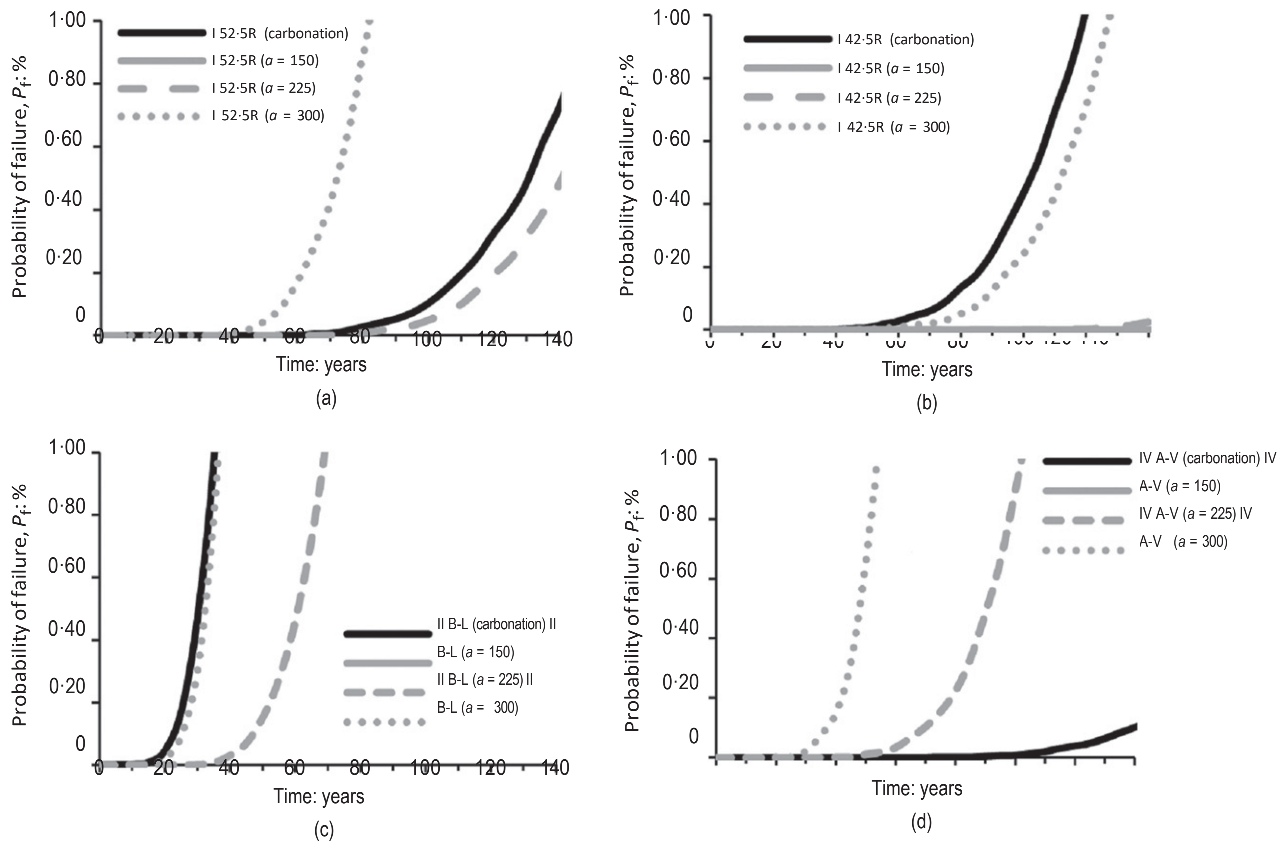

Figure 7. Performance of concrete compositions through time. Carbonation modelling compared with air permeability modelling with variation of parameter *a* – class XC4: (a) CEM I 52·5R; (b) CEM I 42·5R; (c) CEM II/B-L 32·5N; (d) CEM IV/A-V 32·5R

test-based and air permeability test-based modelling. If it is assumed that the carbonation test-based modelling is the refer- ence, in other words, the 'accurate' model, the change in the calibration parameter *a* in the air permeability test-based mod- elling is a viable option to attain convergence between both approaches. However, parameter *b* has an important influence on the comparison of cement type I and II, with cement type IV given the values that are currently endorsed by the analysed standard to each type of cement.

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