LIFETIME PREDICTION OF REINFORCED CONCRETE STRUCTURES IN CARBONATION ENVIRONMENTS CARBONATION MODELLING VS AIR PERMEABILITY MODELLING

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Abstract. This article compares two models for the prediction of lifetimes of reinforced concrete structures in carbonation environments based on different tests: carbonation test-based modelling and air permeability test-based modelling. The study also includes experimental testing of five concrete mixes with different types of cement in order to validate the models using safety factors. The tests included compressive strength, accelerated carbonation and air permeability. Both models are defined in a European standard as being alternative to each other, meaning that their results for the same concrete composition and the same environment should converge. The results show that both current models can scarcely constitute alternative to each other. Design lifetime results are far from similar for each concrete mix and each exposure class. The different nature of each test – accelerated carbonation and air permeability – and their different characteristic such as the scattering of results and the unrelated parameters of the modelling equations are some of the features discussed, including the possibility of using different safety factors as function of the model and definition of possible correlation between tests.

Keywords: air permeability, carbonation, corrosion, design lifetime, partial safety factor method, performance-based approach, semi-probabilistic method.

Introduction

There are currently several conceptual frameworks and prediction models for concrete structures exposed to carbonation and chloride contamination (DuraCrete 2000; Lay *et al.* 2003; BY 50 2004; CS TR 61 2004; Concrete Report 12 2007; Kamaitis 2008; Silva *et al.* 2014; Boutz *et al.* 2008; EHE 08 2008; Kwon *et al.* 2009; NIST 2011; Life-365 2012; Taffes, Sistonen 2013). However, the development of these models may present some difficulties such as the lack of information concerning the scattering of variables. Additionally, there is the difficulty in implementing some of these models along with time consuming procedure (Silva *et al.* 2014; Taffes, Sistonen 2013).

The Portuguese specification LNEC E465 (2009) has introduced a performance-based approach where a required performance is maintained throughout the intended life of the structure, along with the optimization of the lifetime costs (Narasimhan, Chew 2009). This approach is similar to those already in use in other European countries such as Finland (BY 50 2004), Sweden (Concrete Report 12 2007) and Spain (EHE 08 2008).

In the particular case of the performance-based Portuguese specification (LNEC E465 2009), which follows the philosophy of benchmark recommendations and standards (DuraCrete 2000; FIB bulletin 34 2006; ISO 16204 2012) a semi-probabilistic method is used where two different mathematical models:

1. Modelling equations based on CO_2 diffusion tests through the concrete (LNEC E391 1993). The 1st Fick's law is used assuming the CO_2 flow as stationary. The carbonation depth is a function of time and the CO_2 coefficient of diffusion;
2. Modelling equations based on air permeability tests in the concrete (LNEC E392 1993). This model represents the correlation 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 in the open literature for tested concrete composi-

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tions either for carbonation (Marques, Costa 2010; Neves *et al.* 2012b; Marques *et al.* 2013) or for chloride environments (Marques *et al.* 2012).

As regards the second model, based on air permeability tests, this article is the first presenting the comparison with the carbonation-based model based on the same experimental samples and this particular European specification. The correlation between the carbonation depth and air permeability has been assessed by different authors (Nilsson, Luping 1995; Neves *et al.* 2012a), which can give some contribution to the interpretation of the design lifetime results.

In order to assess the convergence between the two models defined by the Portuguese specification LNEC E465 (2009), which has not been done so far, this study quantifies the difference in the design lifetime estimates using both methods for carbonation induced corrosion.

1. Corrosion of reinforcing steel in carbonation environments

Corrosion of reinforcing steel depends directly on the environment surrounding the structures that is, relative humidity, CO_2 concentration and wet /dry cycles (Verbeck 1958; Bakker 1988) The type and quality of materials chosen, compaction and curing of concrete during construction phase, that is porosity of concrete and quantity of matter that can be converted into carbonates is also a factor (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 reinforcing steel, in the case of CO_2 diffusion, until the carbonation depth is equal to the thickness of the concrete cover; and the propagation phase (propagation period t_p), that 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 t_i the lifetime of a structure – $t_L = t_i + t_p$.

European standard EN 206-1 (2000) and Eurocode 2 (EN 1992-1-1 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 article exposure class XC1 is excluded due to its low level of aggressiveness.

2. Reliability criteria for the design lifetime

The performance-based approach and its relationship with the calculation of the design lifetime of reinforced concrete structures is based on reliability criteria established by Eurocode 0 (EN 1990 2002). In this code, 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 scattering in action effects, the uncertainties in resistances and the uncertainties of the chosen model.

Despite the fact that the corrosion effect on reinforced concrete structures vary widely, as regards the consequence levels, the performance-based approach defined in LNEC E465 (2009) considers only the Serviceability Limit States: $P_f < 11.5\%$ (RC3); $P_f < 6.7\%$ (RC2); $P_f < 2.3\%$ (RC3). The Eurocode 0 (EN 1990 2002) considers these limit states exclusively for the reliability class RC2 ($P_f < 6.7\%$).

3. Lifetime modelling

This section describes the main features of the performance-based principles and the currently accepted deterioration model.

3.1. Concrete cover

The Eurocode 2 (EN 1992-1-1 2010) establishes the cover of reinforced concrete structural members and the dispersion of this variable in relation to its execution is also taken into account.

The nominal cover c_{nom} (mm) and the minimum cover $c_{min,dur}$ (mm) are defined by this European code. The first is the value that should be considered in the construction project drawings and specifications:

$$c_{nom} = c_{min,dur} + \Delta c_{dev}, \qquad (1)$$

where Δc_{dev} (mm) is the expected deviation that depends on the quality control, which in the Portuguese case is the recommended value of 10 mm.

According to FIB bulletin 34 (2006), the minimum concrete cover $c_{min,dur}$ may be interpreted as a 5% fractile characteristic value, where $\Delta c_{dev} = 1.645s$, being s the standard deviation of a concrete cover with a Gaussian distribution. Consequently, the standard deviation of the cover corresponds to 6 mm.

The nominal cover c_{nom} is assumed to represent the mean value. However, the minimum concrete cover $c_{min,dur}$ is the one used in the modelling equations of the partial safety factor method (Section 3.5).

3.2. Initiation period t_i based on accelerated carbonation tests

The concept of carbonation resistance R_{C65} expressed by performance-based specification (LNEC E465 2009), corresponds to the ratio between the amount of CO_2

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} (Eqn (2)) results from the laboratory results through an accelerated process with a concentration of CO_2 C_{accel} of 90×10^{-3} kg/m³ (LNEC E391 1993). The duration of testing is t_1 and the subsequent carbonation depth X_1:

$$R_{C65} = \frac{2\,C_{accel}\,t_1}{X_1^2} = \frac{2\,C_{accel}}{k_a^2}. \tag{2}$$

The performance-based specification (LNEC E465 2009) includes the equation that expresses the CO_2 diffusivity of hardened concrete throughout time – carbonation depth x, according to Eqn (3):

$$x = \sqrt{\frac{2 \times \Delta C}{R_{C65}}}\,t\,\sqrt{k_0 k_1 k_2}\left(\frac{t_0}{t}\right)^n, \tag{3}$$

where $\Delta C = 0.7 \times 10^{-3}$ kg/m³ is the difference of CO_2 concentration between the exterior and the carbonation front, k_0 equals 3 and is a constant value that takes into account the testing method and conditions (LNEC E391 1993), k_1 considers the presence of relative humidity (LNEC E465 2009), k_2 quantifies the cure influence: 1.0 for normalized cure and 0.25 for a 3 day period of cure (LNEC E465 2009), t_0 is the reference period = 1 year and n is the parameter that quantifies the wet/dry cycle influence in time (LNEC E465 2009). Table 1 shows the values of parameters k_1 and n for all exposure classes.

The initiation period t_i is expressed as follows:

$$t_i = \left[\frac{R_{C65}\,c^2}{1.4 \times 10^{-3}\,k_0\,k_1\,k_2\,t_0^{2n}}\right]^{\frac{1}{1-2n}}. \tag{4}$$

Table 1. Values of k_1 factor and n factor

	XC1	XC2	XC3	XC4
k_1	1	0.2	0.77	0.41
n	0	0.183	0.02	0.085

3.3. 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 that above (Section 3.2).

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

Following this principle, Eqn (5) was written to calculate the carbonation depth:

$$x = \left(\frac{150^{2.5}\,t^{2.5p}\,m.KT \times 10^{16}}{b^{1.25}}\,k_2\right)^{\frac{1}{2.5}}, \tag{5}$$

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/m³) is the calcium oxide of the hydrated cement matrix of the concrete that depends on the type of binder used and on the exposure class. The variable KT is the coefficient of air permeability of the concrete cover in exposure humidity conditions and it depends on m and therefore on the exposure class.

The equation in terms of t_i is expressed as follows:

$$t_i = \left(\frac{b^{1.25}.c^{2.5}}{150^{2.5}\,m.KT \times 10^{16}}\right)^{\frac{1}{2.5p}}, \tag{6}$$

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

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

RH (%)	$m*$	p	b (kg/m³) CEM I**	b (kg/m³) CEM II/B	b (kg/m³) CEM IV
70 (XC3)	0.725	0.48	460	350	230
80 (XC4)	0.347	0.42	485	360	240
90 (XC2)	0.159	0.33	535	410	265

Notes: *tests were conducted on specimens in equilibrium with RH = 65% instead of RH = 60%. The values of m were changed proportionally.
**also applicable to CEM II/A-L.

3.4. Propagation period t_p – corrosion modelling

The propagation period corresponds to the beginning of corrosion of steel reinforcement until a certain level of deterioration, which can result in crack formation due to steel increase of volume, delamination of concrete cover or rupture of steel bars due to loss of section.

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

Table 3. Minimum propagation periods from corrosion start until cracking (LNEC E465 2009)

Target life t_g	t_g = 50 years	t_g = 100 years
Exposure class	t_p estimated (yrs)	t_p estimated (yrs)
XC1	>100	>100
XC2	10	20
XC3	45	90
XC4	dry region 15 humid region 5	dry region 20 humid region 10

Specification LNEC E465 (2009) defines the minimum values of t_p, based on Faraday's law and empirical equations, that should be added to the design values of the initiation period t_i. Table 3 presents the minimum propagation periods for each exposure class and the target periods of 50 and 100 years.

3.5. Partial safety factor method

For the modelling of the initiation period, the partial safety factor method defined by the performance-based specification LNEC E465 (2009) is carried out by a deterministic calculus where the probabilistic nature of the problem is taken into account using reduction factors (semi-probabilistic approach).

The implementation of the partial safety factor method starts with the definition of the values of each variable in the modelling equations (Eqns (4) and (6)) in either model: carbonation-based tests or air permeability-based tests.

Some of these variables consist of parameters defined by the specification (LNEC E465 2009) based on *in-situ* and laboratory tests and corresponding calibration. Except the concrete cover, all variables are quantified in the equations with their mean value. As explained above (Section 3.1), in view of the quality control of the execution of the reinforced concrete structures, the additional cover thickness may or may not be defined in the design stage.

In this specification (LNEC E465 2009) it is assumed that the additional 10 mm are required and should therefore be specified in the design stage. However, in both models, for the estimation of the initiation period the deterministic calculus considers the cover characteristic value, $c_{min,dur}$ (Section 3.1).

The design lifetime t_L is then calculated through the following equation:

$$t_L = \frac{t_i}{\gamma} + t_p ,$$ (7)

where t_i is the initiation period (obtained from Eqns (4) and (6), depending on the model), γ is the safety factor according to LNEC E465 (2009) – 2.0 (RC1), 2.3 (RC2) or 2.8 (RC3) and t_p is the propagation period given in Table 3 considering the crack formation as the limiting criterion.

In the present study, the determination of the design lifetime t_L using the performance-based approach is carried out considering the reliability class RC3 (failure probability ≤2%) for the exposure classes XC2, XC3 and XC4. The concrete cover value was chosen to following the limits of the prescriptive specification (LNEC E464 2009) for a 50 year target life t_g.

4. Experimental program

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

The performance of these compositions was analysed regarding the testing results, as to compressive strength (EN 12390-3 2003) – performed at CDAC – and as to accelerated carbonation depth (LNEC E391 1993) and air permeability (LNEC E392 1993) – performed at ESTB – Polytechnic Institute of Setúbal.

4.1. Concrete mixes

Considering the exposure classes XC2, XC3 and XC4, the concrete mixes were made in order to respect the limits of the specification LNEC E464 (2009) with respect to water/cement ratio, cement dosage, and cement type.

For each concrete mix the used cements comply with the European standard EN 197-1 (2000). Table 4 shows the cement types and corresponding specific surface (Blaine test), whereas Table 5 presents the constituents of each composition designated according to the cement type.

4.2. Tests procedures and results

Prior to the planned tests, the specimens of all concrete mixes were subjected to specific conditioning in accordance with related standards and laboratory procedures.

For the compressive strength tests, samples were subjected to wet curing of 100% of relative humidity (RH) until the age of 28 days.

With regard to accelerated carbonation tests, the conditioning comprised a wet curing (RH = 100% at 20±2 °C) of 14 days after the mixing of the specimens followed by a period of 14 days of dry curing in an environment of 50±5% of relative humidity and 20±2 °C. At

Table 4. Cements and properties

Cement type	Constituents	Ignition loss	Insoluble Residue	Blaine (cm²/g)	Comp. strength 28d (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
CEM IV/A V 32,5R	>69% K 26% FA	2.3%	26.3%	4292	44.3

Note: K – clinker; LF – limestone filler; FA – fly ash.

Table 5. 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

the age 28 days all the specimens were introduced in the carbonation chamber.

In the case of the air permeability tests, the conditioning of the specimens included as well a wet curing period of 14 days at 100% RH and 20±2 °C and the following 14 days at 65±5% RH and 20±2 °C.

For each concrete mix 18 specimens were produced for the three tests that were previously planned.

4.2.1. Compressive strength

The specimens used for the compressive strength tests were cubes with 150 mm side length and the test itself was carried out according to the definitions of EN 12390-3 (2003).

4.2.2. Accelerated carbonation

In this case the concrete specimens were discs with 100 mm diameter and 50 mm of thickness following the criteria of LNEC E391 (1993).

After the 28 days of conditioning, all the specimens were placed in the carbonation chamber at 20 °C and 65% RH and a CO_2 concentration of 5%. For each concrete mix there were four sets of specimens 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 days after being subjected to accelerated carbonation and then broken in two halves and tested with a solution of 0.5% of phenolphthalein in alcohol (Fig. 1).
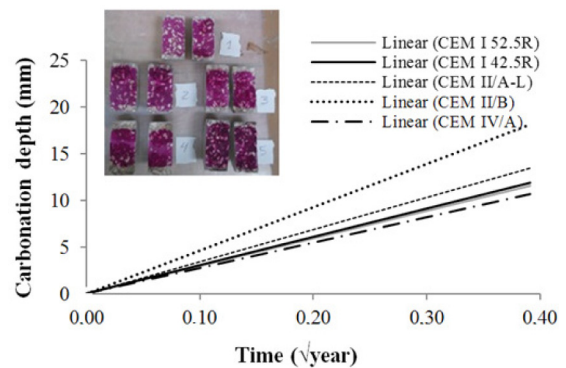

Fig. 1. Results of the accelerated carbonation tests

4.2.3. Air permeability

The specimens prepared for the air permeability tests (Fig. 2) were concrete discs with 150 mm diameter and 50 mm of thickness following the criteria of LNEC E392 (1993) using the Torrent Permeability Tester (PROCEQ).

4.2.4. Tests results

The results of the tests are presented in Figures 2 and 4 and Table 6 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 vs square of time in

Table 6. Concrete experimental characterization. Tests results at the age of 28 days – mean values (coefficient of variation – CoV for R_{C65} and KT)

Concrete mix	f_c (MPa)	k_a (mm/√yr)	R_{C65} (kg yr/m⁵)	KT (10^{-16} m²)
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.
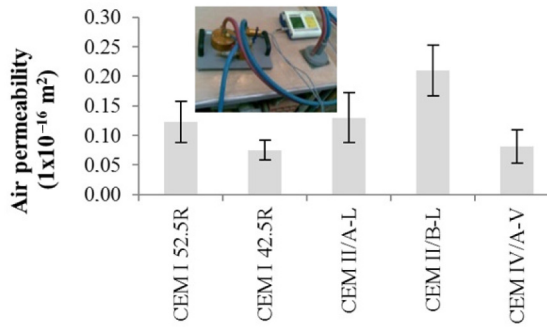
Fig. 2. Results of the air permeability tests

mm/√year) and carbonation resistance R_{C65} (Eqn (2) in [kg/m³]/[m²/year]).

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

5. Design lifetime results and discussion

In order to respect the fundamentals of the exposure classes XC2, XC3 and XC4 for a target period of 50 years, a minimum concrete cover $c_{min,dur}$ of 25 mm is used for classes XC2 and XC3 while for class XC4 the value used is of 30 mm. The chosen reliability class is RC3, which means a maximum probability of failure of 2.3%. All concrete mixes were defined accordingly (Table 5).

In the present analysis, in addition to the inherent conditions of the specific exposure classes, a normalized cure of the reinforced concrete elements is considered and the propagation period is defined as a fixed value following the premises of the performance-based specification (LNEC E465 2009).

5.1. Accelerated carbonation modelling vs Air permeability modelling

The modelling results of the design lifetime t_L, alongside with the initiation and propagation periods − t_i and t_p − are presented in the graphs of Figures 3, 4 and 5. The modelling results are shown in years for the mathematical model that is based on the equations and tests regarding

the accelerated carbonation and the five concrete mixes with different types of cement – upper half – and in the lower half of each graph the results concerning the modelling equations based on air permeability tests.

Being the purpose of the present study the comparison of two methods that constitute an alternative to one another, as can be seen from Figures 3 to 5, it seems variable the convergence of results as regards the design lifetime results t_L, especially if the exposure classes XC2 and XC4 are considered.

As regards the exposure class XC3, the modelling results of the design lifetime t_L of both models are closer between each other. However, in this class, if the results of the initiation period t_i are analysed it is evident that there is an equivalent trend in relation to the exposure classes XC2 and XC4. The reason for this has to do with the fact that for 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 lifetime. Comparatively, for classes XC2 and XC4 the contribution of t_p is almost negligible for t_L.

Subsequently, the question of the irregular convergence is also observed for class XC3, considering the
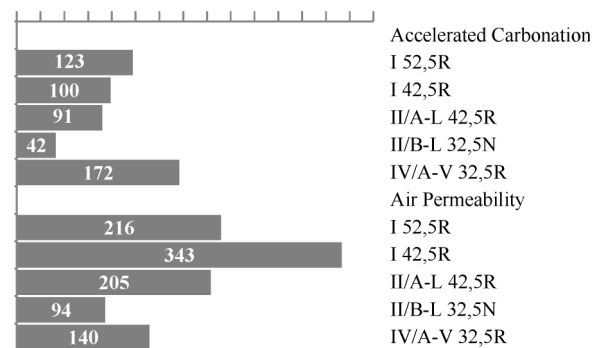
Initiation period t_i - years

Fig. 4. Design lifetime for target period of 50 years, by accelerated carbonation and air permeability methods, for the exposure class XC3
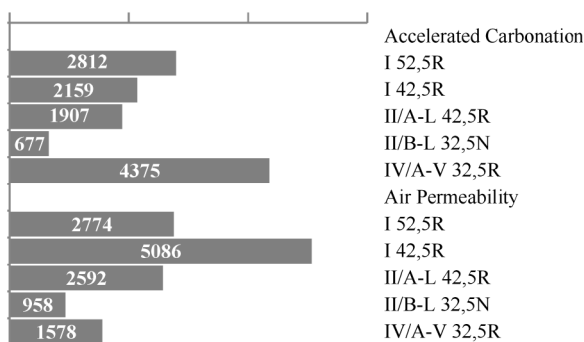
Initiation period t_i - years

Fig. 3. Design lifetime for target period of 50 years, by accelerated carbonation and air permeability methods, for the exposure class XC2
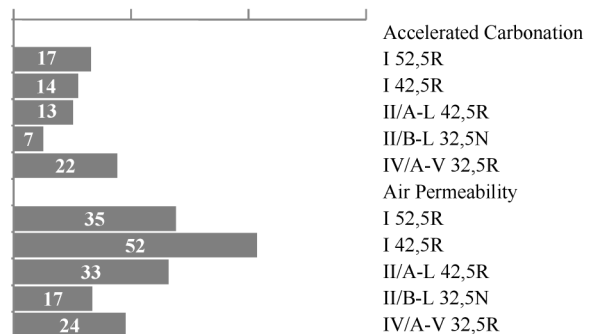
Initiation period t_i - years

Fig. 5. Design lifetime for target period of 50 years, by accelerated carbonation and air permeability methods, for the exposure class XC4 – humid region
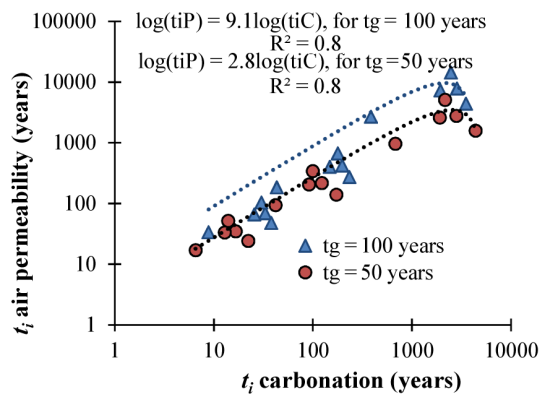
Fig. 6. Results of initiation period according to accelerated carbonation tests (*x-x*) and air permeability tests (*y-y*) for XC2, XC3 and XC4, for t_g = 50 and 100 years

results of the initiation period, where the influence of the tests and equations of each model takes part.

In order to quantify the difference between both models, Figure 6 presents the initiation period according to accelerated carbonation tests (*x-x*) and air permeability tests (*y-y*) for t_g = 50 and 100 years. Results show that there is a logarithmic correlation between t_{iC} and t_{iP} using those two different tests. It is shown that the logarithmic value of t_{iP} is almost 3 times the logarithmic of t_{iC} for a target period of 50 years and 9 times if the target period is about 100 years. Figures 3 to 5 help in finding possible convergence. As referred before, due to the relevant influence of t_p, the ratio for the design lifetime in class XC3 presents values that may be considered not far from 1.0 (perfect match) (Fig. 4), varying from 0.74 to 0.97, the exception is the concrete mix CEM I 42.5R with t_{LC}/t_{LP} = 0.61. Nonetheless, the ratio t_{iC}/t_{iP}, which relates to the initiation period, presents values far from 1.0 varying from 0.27 to 0.48. As an exception, concrete mix CEM IV/A presents ratios t_{iC}/t_{iP} between 0.93 and 0.97. For class XC2 the ratios vary from 0.71 to 1.01 which correspond to a relatively fair convergence, except for concrete mix CEM IV/A where the ratio is of 2.77. In the case of class XC4 only CEM IV/A show a ratio not far from 1.0 (1.23) while the remaining mixes present ratio values between 0.29 and 0.57 which reveals a significant distance between both models.

Taking into account the two parts of the presented study – i) the experimental work and ii) the calculus and analysis of the design lifetime – it is reasonable to state that according to both sets of results, those of laboratory tests and the ones of the modelling calculus, the two mathematical models do not provide similar results in most cases. The results presented in Figure 6 show that there is a logarithmic correlation between t_{iC} and t_{iP}. However, these results do not mean that there is a convergence between both test methods, but can help in the estimation for initiation period.

At this stage, it is possible to discuss which might be the main causes of such a differences between some of the results of both models.

Primarily, it should be borne in mind that the principle that supports the definition of the safety factor value γ defined by LNEC E465 (2009) relies on lifetime having a lognormal distribution with a CoV of 0.5 (RILEM Report 14 1996). Additionally, these safety factors do not consider any uncertainty related to each of the modelling equations of the initiation period.

Furthermore, three main topics should be regarded as highly influencing the difference between both models:
1. Different equations and consequently possibly different uncertainty levels;
2. Different tests – the nature of the carbonation test involves both physical and chemical processes, while the air permeability test is of physical nature;
3. The scattering of results of the air permeability test is approximately the double of those of the accelerated carbonated tests (Table 5).

Being these three aspects the plausible origin for the differences between the studied models, the one that stands out is topic 3 since it is more tangible in terms of results. In fact, even though the experimental results of the present work may not be sufficient to be representative of such a difference concerning the dispersion of tests results, previous research studies have observed similar problem (Nilsson, Luping 1995; Neves *et al.* 2012a).

Bearing in mind that none of the models can be considered as "more accurate" than the other, in order to analyse to what extent the dispersion of test results is actually affecting the convergence between both models, it is relevant to carry out an analysis in which all the statistical parameters of the experimental data are considered.

5.2. Analysis of the performance of each concrete mix

The decision of calculating the design lifetime for the exposure classes XC2, XC3 and XC4 and the chosen five concrete mixes was driven by the simplicity with which the overall analysis can be done. Some results may, yet, be considered "unrealistic", since it seems inaccurate to conclude that any reinforced concrete structure, without significant retrofitting intervention, will last more than 100–120 years.

With regards to the carbonation modelling, the relative performance of the five concrete mixes is similar either test or lifetime results are evaluated. The reason for this has to do with the chemical nature of the test in which the reaction of CO_2 with the hydroxides of the cement paste is assessed.

The analysis of carbonation resistance R_{C65} in Table 6 and the lifetime results in Figures 3 to 5 show that, amongst all mixes, concrete mix CEM IV/A has the best performance while on the opposite side CEM II/B has the lowest results. For CEM IV/A such results may be explained by the combined effect of lower w/c and a more refined porous structure due to the blend of fly ash with clinker, which sustained by the air permeability test result (one of the lowest values.

As to the air permeability modelling, for the performance of the different concrete mixes the direct analysis

of the air permeability tests (Table 6) does not have a direct relation with lifetime modelling results (Figs 3 to 5). Since the test deals uniquely with the air diffusion through the porous structure of the specimens, the model presented by LNEC E465 (2009) includes parameter *b* that takes into account the type of binder used in a concrete composition. Consequently, concrete mix CEM IV/A shows a lifetime value behind concrete mixes CEM I 52.5R, CEM I 42.5R and CEM II/A, despite the first having one of the lowest test results of air permeability. As regards concrete mix CEM I 42.5R, its outstanding performance compared to the other compositions is evident. With an air permeability coefficient similar to that of concrete mix blended with fly ash – KT(CEM I 42.5) = 0.075 × 10^{-16} m^2 and KT (CEM IV/A) = 0.081 × 10^{-16} m^2 – the design lifetime result for concrete mix CEM I 42.5R is, however, substantially higher given the fact that the parameter *b* considered is also higher (Table 6).

Conclusions

The two studied models are based on accelerated carbonation and air permeability tests and were defined to be an alternative to each other using a semi-probabilistic approach, meaning that the design lifetime calculated using both models should have fair similarity.

The modelling results show that globally there is no "reasonable" convergence between both methods which, as discussed above, might be related to the nature of the tests, the different scattering level and the consideration of these combined effects in the adopted safety factors, which are defined with the same value in both models. The results presented in Figure 6 show that there is a logarithmic correlation between t_{iC} and t_{iP} (not a convergence between both values) that can help in the estimation of initiation period.

As regards the prediction of lifetime in environments where is the aggressive agent, given the prevailing option by recommendations and standards of using the models based on accelerated carbonation, there may be the tendency to consider these models as the reference or the "correct" ones. Analysing the results of both models it may be tempting to conclude that it should be the model based on air permeability tests that should meet the results of the one based on carbonation tests. It would not be precipitant, though, to reflect otherwise.

The results of this study show the importance of future discussion for the improvement of the convergence between carbonation test-based and air permeability test-based models, with respect to carbonation induced corrosion.

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