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Reinforced Concrete Durability Design Through a Semi-probabilistic Approach

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Abstract

This study provides a semi-probabilistic approach to durability design of reinforced concrete structures, subjected to carbonation-induced corrosion. The method was developed from an existing approach and using comprehensive data collated from the literature. A statistical model for predicting accelerated carbonation coefficient, using as input variables mix proportions and test conditions was also generated. The performance of the proposed method was assessed and proved appropriate. Besides delivering a more consistent semi-probabilistic method to design for the avoidance of unforeseen carbonation-induced corrosion problems, the developed statistical model to estimate the accelerated carbonation coefficient is a useful tool on the mix design, from the standpoint of conforming with the accelerated carbonation coefficients obtained through the semi-probabilistic method.

Keywords

acceleration, carbonation, multiple linear regression, performance-based design, service life, statistical modeling

1 Introduction

Atmospheric carbon dioxide reacts with alkaline compounds present in the cement paste, forming carbonates, which leads to a decrease in the alkaline nature of concrete [1]. The reduction in alkalinity leads to depassivation of the reinforcement so that it is no longer protected from corrosion [2]. Significant research has been carried out, comprising experimental investigation on carbonation mechanism [3], theoretical models proposed to predict carbonation depth of concrete based on experimental results [4], its practical application and life prediction models [5]. Seigneur et al. [6] used fully coupled two-phase reactive transport modeling focusing on the hydrated C3S paste and low-pH paste of the concrete. Taffese et al. [7] employed machine learning technique while Ta et al. [8] employed semi-empirical technique to predict carbonation of concrete. Auroy et al. [9], inferred that accelerated carbonation at 3% CO_2 could be the representative of natural carbonation.

In fact, over the last decade, several researchers have examined the natural carbonation data to estimate the durability of carbonated concrete structures [10, 11].

Research was carried out on parameters influencing carbonation: relative humidity, temperature, and atmospheric carbon dioxide concentration retrieved through respective Representative Concentration Pathways (RCPs) from the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) [12, 13]. However, Jiang et al. [14] did not agree with the invariant relative humidity hypothesis and did not include relative humidity as a parameter in carbonation depth prediction under a changing climate. Due to its potential to lower carbon emissions and provide durable concrete, accelerated CO_2 curing for building materials has recently attracted more and more interest [15]. Research on CO_2 uptake after four-year natural exposure data and ten-year natural exposure data were reported to assess the CO_2 exchanges during the life cycle of structures [16, 17]. Performance-based design concepts for the durability of reinforced concrete structures against concrete carbonation have been recently developed [18, 19].

In order to obtain better control of corrosion of reinforcing steel, improved procedures for quality control and

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specifications for proper combinations of concrete quality and reinforcement cover during construction are very important. Investors began to foresee increased and controlled durability beyond what is still widely practiced, this means moving from deemed-to-satisfy approaches towards performance-based design, even with a small increase in additional costs [20].

In this sense, Neves et al. [21] provided a simple semi-probabilistic approach to the service life design of reinforced concrete structures with respect to carbonation-induced corrosion. They conducted laboratory research on accelerated carbonation and field studies on natural carbonation in an attempt to determine design performance parameters, such as carbonation rate. Further, they studied the correlation between accelerated and natural carbonation. This correlation was compared with results from other studies comprising accelerated and natural carbonation tests, available by then.

However, the remark from Köliö et al. [22], questioning the non-availability of data from repeated measurements of natural carbonation of the same concrete at a certain interval of time in both indoor and outdoor environment, remains relevant. The objective of this work is to address this gap and to conduct performance-based durability design. The developed methodology still incorporates the interrelation between safety factor and reliability, by means of updating the approach proposed by Neves et al. [21], contributing at the same time for a desirable clarification of the relationship between accelerated and natural carbonation. This aspect is of interest within the frame of international standards and recommendations.

For this purpose, natural carbonation results, from successive measurements in time, were collected from the literature. The same was done for accelerated carbonation results. As no comprehensive studies comprising both types of carbonation were found and a relationship between natural and accelerated carbonation was still sought, a statistical model was developed with the aim of estimating accelerated carbonation coefficients for the mixes tested under natural carbonation conditions.

2 Natural carbonation results

Huy Vu et al. [23] performed a unique international inter-laboratory study on the impact of different climates on resistance of concrete to natural carbonation. Concrete specimens were cast in France and shipped to four academic research laboratories in the USA, Canada, India and China to study the role of local climatic conditions on the progress of natural carbonation for five years. EN 206-1 establishes four exposure classes for carbonation-induced corrosion, with XC3 and XC4 representing outdoors sheltered and unsheltered circumstances, respectively [24].

For the current investigation, results from mixes with Ordinary Portland cement (OPC) and w/c ratios of 0.45, 0.55 and 0.65, and tested in Chennai (India) were selected. This was because OPC is considered the reference binder concerning carbonation-induced corrosion [25] and Chennai was the site with the most complete range of times of exposure (1, 2, 3 and 5 years). Carbonation depth was assessed using a 0.5% phenolphthalein solution, sprayed over a freshly broken surface and measuring the depth of the colorless reaction zone.

From the experimental carbonation depth results, the carbonation coefficient is found by using Tuutti's model [26]:

$$X = \sqrt{t} \,, \tag{1}$$

where X is the carbonation depth (mm), t is the duration of CO_2 exposure (year) and K is the carbonation coefficient (mm/year$^{0.5}$).

The mean and standard deviation of the natural carbonation coefficient for the sheltered conditions are 2.83 and 0.96 mm/year$^{0.5}$, respectively, while for unsheltered conditions the mean and standard deviation of the natural carbonation coefficient of the various cases considered are 2.31 and 0.83 mm/year$^{0.5}$, respectively.

3 Accelerated carbonation results

Cui et al. [27] investigated the relationship between carbonation depth and CO_2 concentration by subjecting concrete of different grades to five different CO_2 concentration levels (2, 10, 20, 50 and 100 % by volume). Details of the concrete mixes considered in that study are recapped in Table 1.

After 28 days of curing in a controlled environment, concrete specimens were exposed to an accelerated carbonation test according to GB/T50082-2009 [28]. The test conditions were 20°C, 70% relative humidity and different CO_2 concentration levels (2, 10, 20, 50 and 100% by volume) [27]. Carbonation depth was measured by spraying 1% phenolphthalein solution on a freshly broken surface after 7, 14, 28 and 56 days of exposure in the carbonation chamber. From the experimental carbonation depth results, the accelerated carbonation coefficient is found by using Eq. (1). As the duration of CO_2 exposure at the carbonation chamber is 7, 14, 28 and 56 days, the corresponding carbonation coefficients were computed and the mean carbonation coefficient, for each mix and CO_2 content, is presented in Table 2.

Table 1 Concrete mix design details from Cui et al. experiments, [27]

Mix code	*w/c*	Ordinary Portland cement (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Water (kg/m^3)	Expected compressive strength (MPa)
G30	0.55	310	739	1203	170	30
G40	0.45	378	715	1158	170	40
G50	0.35	486	670	1100	170	50

Table 2 Mean carbonation coefficient for different mixes and CO_2 concentrations

Mix code	CO_2 concentration (%)	Mean accelerated carbonation coefficient (mm/year$_{0.5}$)
G30	2	12.81
	10	38.92
	20	66.35
	50	78.88
	100	79.88
G40	2	5.21
	10	33.30
	20	51.03
	50	59.01
	100	59.69
G50	2	2.41
	10	15.44
	20	30.02
	50	36.14
	100	38.12

4 Statistical modeling of accelerated carbonation coefficient

The developed statistical model to estimate the accelerated carbonation coefficient is based on a multiple linear regression analysis, that is applied to the results from Cui et al. [27]. A similar approach has already been tried by Silva et al. [29] to estimate natural carbonation coefficients. In this multiple linear regression model, the carbonation coefficient is the dependent variable and water-cement ratio, cement content, expected 28-day compressive strength and carbon dioxide content are the independent variables. Statistical Package for the Social Sciences software (SPSS) was used to build the model. The Stepwise method was used here, which enabled only the statistically significant independent variables to be included in the model [29]. In the model proposed, it is found that the variables considered by ranking of relevance are CO_2 content and *w/c* ratio. Table 3 summarizes the coefficients obtained from the analysis of statistical validity of the regression models.

From the analysis in SPSS, it is inferred that 91.8% of the carbonation coefficient variation is explained by the two variables used and that the model is statistically significant. Table 4 shows the analysis of variance (ANOVA) of the models.

Table 5 presents the linear regression coefficients (B) of the models, and it is found that the significance value is lower than the p-value for all independent variables, which infers that they are able to explain the carbonation coefficient.

Thus, Eq. (2) can be defined to estimate the accelerated carbonation coefficient.

$$k_a = -49.189 + \left(2.336 \times C\right) + \left(117.012 \times \frac{w}{c}\right), \qquad (2)$$

where k_a is the accelerated carbonation coefficient (mm/year$^{0.5}$), C is the CO_2 content (%) and *w/c* is the water-cement ratio (kg/kg).

The model is consistent with the existing concrete carbonation knowledge. The increase of CO_2 content or the increase of water-cement ratio, cause an increase in concrete carbonation (coefficient).

Table 3 Summary of multiple linear regression models

Model	R	R^2	$R^2_{adjusted}$	Standard error of the estimate
1[a]	0.847	0.717	0.677	12.24545
2[b]	0.969	0.939	0.918	6.16649

a) Predictors: (Constant), CO_2 concentration
b) Predictors: (Constant), CO_2 concentration, w/c ratio

Table 4 ANOVA table of the models

Model		Sum of squares	Degrees of freedom	Mean Square	Test statistic - F	Significance level
1[a]	Regression	2663.777	1	2663.777	17.764	0.004
	Residual	1049.657	7	149.951		
	Total	3713.434	8			
2[b]	Regression	3485.280	2	1742.640	45.828	0.000
	Residual	228.154	6	38.026		
	Total	3713.434	8			

a) Predictors: (Constant), CO_2 concentration; b) Predictors: (Constant), CO_2 concentration, w/c ratio

Table 5 Statistics of the models' regression coefficients

Model	Terms	Linear regression coefficient B	Std. Error	Standardized Coefficient Beta	Test statistic -t	Significance level
1[a]	(Constant)	3.466	7.185	0.847	0.482	0.644
	CO_2 concentration	2.336	0.554		4.215	0.004
2[b]	(Constant)	-49.189	11.892	0.847 0.470	-4.136	0.006
	CO_2 concentration	2.336	0.279		8.370	0.000
	w/c ratio	117.012	25.175		4.648	0.004

a) Predictors: (Constant), CO_2 concentration; b) Predictors: (Constant), CO_2concentration, w/c ratio

5 Relationship between natural and accelerated carbonation

The accelerated carbonation coefficients, of the mixes from where the natural carbonation coefficients were obtained, were estimated through Eq. (2), considering a content of CO_2 in accelerated conditions equal to 5% in volume, as specified in the Portuguese standard for accelerated carbonation testing [30] and adopted in different studies [31, 32], while within ±1% difference from other standards and research works [33, 34].

Figs. 1 and 2 show the relationship between the estimated accelerated carbonation coefficients and natural carbonation coefficients under sheltered and unsheltered conditions.

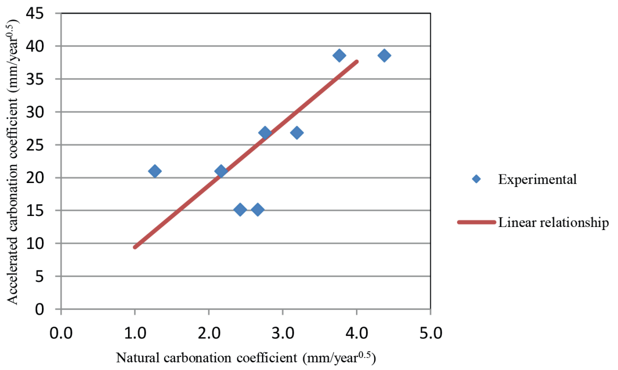

Fig. 1 Relationship between natural and accelerated carbonation coefficient – Sheltered

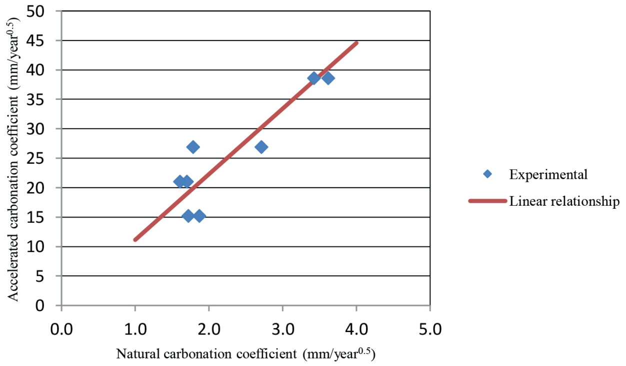

Fig. 2 Relationship between natural and accelerated carbonation coefficient – Unsheltered

Assuming a linear relationship between the accelerated carbonation coefficient k_a and the natural carbonation coefficient, a linear regression with residual analysis has been performed, and the residuals were analyzed for normality using the Anderson-Darling test and are presented in Table 6 [35].

The results concerning acceleration factors obtained in this research are similar to others found in the literature [34, 36]. As a result, the use of the data in Table 6 in conjunction with Eq. (1) appears to be a viable strategy for predicting long-term concrete carbonation in structures from short term (accelerated) carbonation tests. Within this frame, K in Eq. (1), is a parameter that accounts for all factors affecting carbonation. Breaking down those parameters into environmental factors and concrete intrinsic factors, K may be defined as:

$$K = \frac{k_a}{k_e}, \tag{3}$$

where k_a is the accelerated carbonation coefficient (mm/year$^{0.5}$), for tests run under 5% CO_2 content and k_e is a non-dimensional acceleration factor, depending on the exposure condition, being 9.41 for sheltered condition and 11.14 for unsheltered condition (Table 6).

6 Design criteria and model

Probabilistic methods incorporate the use of reliability-based design and the limit state methodology either by full-probabilistic or semi-probabilistic (partial factor method) approaches [37, 38]. Because the partial factors recommended by the deterministic procedures could lead to expensive repairs, Sýkora et al. [39] insisted on realistic verification using partial factors based on the semi-

Table 6 Regression analysis results

Acceleration factor	Sheltered	Unsheltered
Predicted	9.41	11.14
95%confidence interval	[7.12; 11.7]	[9.55;12.7]
Pearson's r	0.7832	0.8956

probabilistic approach. Following Neves et al. [21], in a semi-probabilistic design for a limit state of depassivation, the restriction of failure probability may be defined by:

$$\frac{R}{\gamma_R} - \gamma_S \times S > 0 \,, \tag{4}$$

where R, S are the thickness of reinforcement cover and the carbonation depth, respectively, and γ_R, γ_S are the corresponding safety factors.

Concerning cover depth, the approach adopted by Neves et al. [21] will be followed, i.e., the design value for cover, instead of dividing the nominal value by the safety factor, will be the nominal value minus a safety margin:

$$c_d = c_{nom} - \Delta_c \,, \tag{5}$$

where c_d is the reinforcement cover value considered in design, c_{nom} is the nominal reinforcement cover, i.e., the specified cover for construction, and Δ_c is the reinforcement cover safety margin, usually 10 mm [21].

Neves et al. [21] quantified the safety factors related to carbonation depth using the Monte Carlo technique in which the reinforcement cover was considered a deterministic variable and the parameters k_a and k_e from Eq. (3) were assumed to be random variables. Incorporating the safety factors as per Neves et al. [36], Eqs. (1) and (4) can be re-written as:

$$k_a < \frac{c_d \times k_e}{\gamma_S \sqrt{t_{SL}}} \,, \tag{6}$$

where k_a is the accelerated carbonation coefficient (mm/year$^{0.5}$), concerning tests run under 5% CO_2 content, c_d the reinforcement cover design value (mm), according to Eq. (5), k_e is the acceleration factor being 9.41 for sheltered condition and 11.14 for unsheltered condition (from Table 6), γ_S is the safety factor, 1.00 for sheltered and 1.25 for unsheltered condition [21] and t_{SL} is the specified service life (year).

The maximum accelerated carbonation coefficients, allowed to ensure a service life free of carbonation-induced corrosion, obtained by applying the model - Eq. (6) - for nominal reinforcement cover ranging from 15 mm to 40 mm and a service life between 10 and 120 years are presented in Figs. 3 and 4, for sheltered and unsheltered conditions, respectively.

7 Comparative analysis

The developed model is compared with a similar model, previously proposed and validated by Neves et al. [21]. Taking advantage of having also a statistical model that relates the performance indicator (accelerated carbonation coefficient) with the most popular design parameter of the prescriptive approach (w/c ratio), used in several standards, as the European standard EN 206-1 [24] and its national annexes and the ACI 318 [40], the developed model is compared with a case of prescriptive approach: the National Annex to EN 206-1 for Portugal [25]. Considering the later, the scenarios presented in Table 7 were adopted for the comparative analysis. The adopted nominal covers are those required by the National Annex to EN 206-1 for Portugal [25], for the respective exposure condition and target service lives.

The maximum allowed k_a from Eq. (6) and from the model proposed by Neves et al. [21], for the different scenarios are presented in Table 8. The values are quite similar for sheltered conditions, but stricter for the new model, being this trend more evident for the values

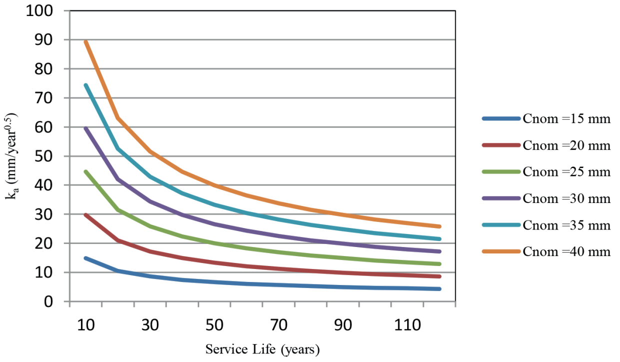

Fig. 3 Limit k_a for sheltered condition

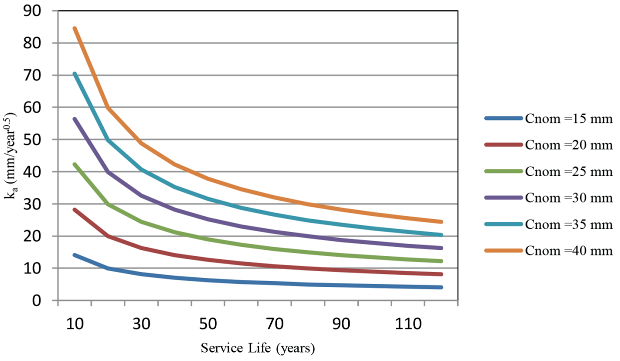

Fig. 4 Limit k_a for unsheltered condition

Table 7 Scenarios for the comparative analysis

Scenario	Intended service life (years)	Exposure condition	Nominal cover (mm)
A	50	Sheltered	35
B	100	Sheltered	45
C	50	Unsheltered	40
D	100	Unsheltered	50

Table 8 Maximum allowed k_a (mm/year$^{0.5}$)

Scenario	Eq. (6)	Neves et al. [21]
A	33.3	35.0
B	32.9	34.7
C	37.8	50.9
D	35.6	48.0

Table 9 Maximum allowed *w/c*

Scenario	Eq. (6) + Eq. (2)	E-464 [25]
A	0.60	0.60
B	0.60	0.60
C	0.64	0.60
D	0.63	0.60

concerning unsheltered conditions. The now proposed model may be seen as an update of the model proposed by Neves et al. [21], to overcome the afore mentioned issues, incorporating at the same time recent data available in the literature, through the update of the acceleration factor. As lower acceleration factors were obtained in the present investigation, than by Neves et al. [21], it is natural that stricter accelerated carbonation resistance is required.

Another interesting point is that even though values from both models are not in accordance with the rating for the severity of exposure conditions defined by EN 206-1 [24], which may appear as contradictory, it shall be noticed the adopted scenarios considered more 5 mm of cover depth for unsheltered conditions than for sheltered conditions, and the service lifetime is a result of not only the quality of the cover concrete but of both the quality and depth of reinforcement cover.

Now, considering the values from Eq. (6), presented in Table 8 and applying Eq. (2), the maximum allowed *w/c* ratios are computed. For the sake of coherence, the CO_2 content in Eq. (2) was kept 5%, as in the study of the relationship between natural and accelerated carbonation. These values are presented in Table 9, together with the values set in E-464, that is the National Annex to EN 206-1 for Portugal [25].

Interestingly, for sheltered exposure conditions the limit w/c ratios obtained through the models match those set by E-464 [25], what pays in favor of the validation of the developed model. Yet, for unsheltered conditions, the limit w/c ratios obtained through the models are softer than those set by E-464 [25], which is quite typical of performance-based approaches versus prescriptive approaches. Actually, concerning limits for *w/c* ratios, E-464 [25] is lenient when compared with its mother-standard, the EN 206-1 [24]. Such lenience is grounded on the meanwhile acquired experience-based knowledge. This trend to allow higher w/c than EN 206-1 [24] is also present in the Swiss standard, even though only for sheltered conditions [41]. Nevertheless, the applied methodology allows the consideration of even higher w/c, what pays in favor of concrete production cost and workability.

It is worth to recap that, even if the proposed method leads to an equivalent solution to one obtained by a simpler approach, as the prescriptive E-464 [25], like it was found in this comparative analysis, the proposed method has a clear advantage of being more flexible, once it is not bound to a limited number of combinations service lifetime-nominal cover [42] allowing the designer to place more emphasis either on the quality or on the thickness of concrete cover to reinforcement. Furthermore, despite being recognized that *w/c* may fail to constitute a reliable concrete durability indicator [43], it still can be used as a guideline for concrete mix design, to attain the required k_a [44]. In this sense, Eq. (2) constitutes another feature of the present investigation.

8 Conclusions

One of the durability problems in reinforced concrete structures is the natural carbonation of concrete, which depends on both the materials' characteristics and the surrounding environment. The statistical model proposed to predict accelerated carbonation depth assumes a linear relationship between the variables and the carbonation coefficient. In this relationship, a determination coefficient of 0.918 was obtained, indicating an excellent ability of the model to explain the variation of the carbonation coefficient with the water-cement ratio and with the CO_2 concentration. Using the modeling results and natural carbonation results, acceleration factors were obtained by regression analysis for both sheltered and unsheltered conditions. The correlation coefficients obtained from the regression analyses were 0.78 and 0.90 for sheltered and unsheltered conditions, respectively. These are substantially higher than those found in the literature, establishing a more robust background for the development of the durability design approach.

In the development of the durability design approach, the acceleration factors were incorporated in the semi-probabilistic method to establish limit accelerated carbonation coefficients, when aiming to attain an intended service life. The method is based on Fick's first law and uses a safety factor, which is related with the target reliability, as well as with the environmental conditions. The developed method was validated through comparative analyses. A comparative analysis with a similar method, formerly proposed, revealed similar results for sheltered conditions (near 5% differences) and stricter specifications for unsheltered conditions (25% lower accelerated carbonation coefficients are required). The other comparative analysis was with a standardized prescriptive approach. The comparative factor was the limit water-cement ratio set by both approaches. For sheltered conditions, the values are equal, while for unsheltered conditions the herein developed approach allows higher water-cement ratios (5% higher), confirming the claimed advantage of using performance-based instead of prescriptive approaches. It is considered that these comparative analyses prove that the herein proposed method can be applied to establish carbonation performance requirements.

Given the circumstances, the proposed model constitutes the answer to a pressing update of the one to whom it was compared, using more complete data, made available by the research carried out in the 10 years that have passed since its disclosure. Yet, a side model is made available, to help in the design of concrete mixes conforming to target accelerated carbonation coefficients defined through the main model. Further, upon the current trend to use less carbon-costly binders, another update of the model is under preparation, considering limestone calcined clay cement (LC3) concretes.

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