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RESEARCH ARTICLE

Evaluation of service-life prediction model for reinforced concrete structures in chloride-laden environments

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Abstract

Reinforced concrete structures are subjected to several degradation processes that often occur early, especially due to reinforcements corrosion. Therefore, the use of representative models for an accurate service-life prediction of reinforced concrete structures becomes indispensable. Thus, this study is aimed at evaluating the model proposed by Andrade to efficiently predict the chloride penetration in concrete structures. In addition, the input variables of this model, as well as the challenges in obtaining them are analyzed. Andrade's model was applied in some case studies to verify their efficiency in predicting the chloride penetration in reinforced concrete structures in marine environments. The results indicate that for data with small exposure times, the model yielded similar responses to the chloride penetration in situ, with good results within an error range of 35%, associated with a maximum difference of only 4.6 mm between observed and calculated values. For the data with higher exposure times, the differences were significant, indicating the need for an alteration in order to best determine the increase in surface chloride concentration over time. Thus, it is suggested that the model undergoes modifications, mainly in relation to two fundamental aspects, (i) adopt the growth of the chloride surface concentration over time and (ii) consider the variability of the concrete characteristics and exposure conditions through a probabilistic approach.

Keywords Concrete · Service-life prediction · Chloride penetration · Modeling

1 Introduction

Concrete is the most widely used construction material in the world, mainly because of its versatility and relatively low cost [1]. The ability of concrete to withstand the degradation processes such as weathering, chemical attack, and abrasion demonstrates its durability [2], which is defined by three main factors: constituent materials; design, construction, and maintenance stages of the structure; and the environmental conditions of exposure [3].

Because of the degradation problems observed in concrete, concerns on durability and improving the service-life of concrete structures are constantly increasing. This is mainly due to the substantial costs of repair and replacement of these structures, which continue to increase. It is estimated that about 40% of the resources spent by the construction industry in developed countries is toward repair and maintenance of existing structures [4]. In 2004, England, France, and Germany spent about 50% of their total investment toward the construction sector [5]. In the United States, the annual costs associated with metallic corrosion amount to 3.1% of the gross domestic product of the country, which corresponds to a value of 276 billion dollars. Of this, 22.6 billion is spent toward the infrastructure sector, and 37% toward the repair costs of corrosion in the bridges of American transport system [6].

In addition, the standards [7–10] are more rigorous, with regard to the construction of more durable concrete structures and establishing minimum performance parameters

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related to durability (usually measured over the structure service-life). Durability corresponds to the period between commencing of building for operation and the time it ceases to serve its purpose. In this context, the performance criterion related to durability, established by the ABNT NBR 15575 [10] standard, defines a minimum service-life of 50 years for the structural systems of residential buildings; however, it does not provide forecast models for estimation of the service-life of these systems.

Among the mechanisms of degradation that affect the service-life of concrete reinforced structures, reinforcement corrosion is the important problem [11–14], which causes major damage to these structures. These damages are manifested in the form of cracks, displacement of concrete cover, reduction in the cross section, and loss of adhesion of the main reinforcement [15], which may lead to a compromise in structural safety over time [16].

The problem of the degradation of reinforced concrete structures due to reinforcements corrosion is of greater concern in coastal regions, due to the high aggressiveness of this environment caused by the presence of chlorides. As an aggravating factor, the Brazilian coast is 7367 km [17] and many of the Brazilian capitals are located there, such as Fortaleza, Natal, João Pessoa, Recife, Maceió, Salvador, Vitória, Rio de Janeiro and Florianópolis.

In most of the studies that evaluate the behavior of reinforced concrete against the action of chlorides, the corrosive process is accelerated by (i) applying an external current [18–20], (ii) adding substances such as $CaCl_2$ or NaCl in the concrete mixture [21–23] and (iii) through wetting–drying cycles with NaCl solution, since the time required for the phenomenon to occur naturally is not available. These accelerated tests receive a lot of criticism because they are characterized by the application of very aggressive conditions that aim to minimize the time to obtain the results and that usually do not match the real conditions of exposure to the natural phenomenon. Usually, they are used to comparatively analyze the performance of different materials and, as conditions are applied to accelerate the corrosive process, it becomes difficult to use them to predict the service life of real structures. In parallel, some studies have been carried out in marine environments, with natural exposure conditions [24–27]. These studies are considered more adequate to evaluate the chloride penetration in concrete and to predict the service life of this type of structure, although they require higher periods of exposure than those required in accelerated tests.

The first attempt for modeling the mechanism of reinforcement corrosion was represented by the model proposed by Tuutti in 1982 [28], which subdivides the corrosive process into the initiation and propagation periods. The initiation period, corresponding to the service-life of the structure, is defined as the time when the aggressive agents diffuse through the concrete cover to reach the reinforcement. The propagation period corresponds to the time necessary for the deterioration to intensify, to cause an acceptable limit of damage. In order to predict the service-life of concrete structures, it is necessary to develop a representative model of degradation which, in the case of this research, is associated with the initiation period of reinforcement corrosion.

There are several models in the literature for estimating the service life of concrete structures in relation to reinforcements corrosion triggered by chlorides [29–36]. However, the vast majority of the aforementioned models are complex, of low practical applicability and many require input data that are usually determined through laboratory tests such as the diffusion coefficient, which is usually obtained through accelerated tests.

In this context, we highlight the model for the prediction of service life of concrete structures proposed by Andrade [37–39], which has simple input data and easy to obtain, such as w/c ratio of the cement matrix, cement type, type of mineral addition used, among others. This model was obtained through a Focus Group experiment conducted with specialists in the area of materials durability structures and technology. In 2001, when Andrade published his work, there were few field data available for the validation of his model. In this way, it is still necessary to perform the analysis of the application of the same in different structures, in order to validate it based on the greater number of possible combinations.

The lack of data on the penetration of chlorides in concrete structures exposed in a marine atmosphere zone during high exposition periods, which makes it difficult to monitor the progress of the critical concentration of chlorides along the concrete depth and, consequently, the validation of the model proposed by Andrade. In relation to the previous works that evaluated the application of the model in question, it was verified that the behavior of the model was consistent with the results of experimental investigations accomplished by other researchers [38–40].

In order to complement the analysis and validation of the Andrade's model, this work had as objective to evaluate the effectiveness of the model proposed by Andrade in relation to the predicted service life of concrete structures exposed in a marine atmosphere zone. For this, data were selected in the literature, in order to verify the deviation of the depth of the critical chloride concentration calculated through the model in question in relation to that observed. In addition, the performance of the Andrade's model was compared to Fick's 2nd Law, since the main transport mechanism for chloride ions in concrete is diffusion, which can be modeled using Fick's second law of diffusion.

2 Service-life prediction models

Various models are available for the prediction of service-life of reinforced concrete structures that consider the reinforcement depassivation by chlorides [18–23, 41]. The proposed formulations vary in complexity, but most are based on the assumption that part of the process is controlled by diffusion [38]. Thus, most of these models result from the resolution of the Fick's 2nd Law, which considers different boundary conditions [42]. There are, however, some models that are explained by other methods and hypotheses; for example, models based on laboratory or field data and models based on the experience of experts. The analytical solution of the Fick's 2nd Law, which adopts the diffusion coefficient and surface chloride concentration constant, is presented in Eq. 1.

$$\mathrm{C}\,(\mathrm{x},\mathrm{t}) = \mathrm{C_i} + \left(\mathrm{C_{sa}} - \mathrm{C_i}\right)\mathrm{erfc}\,\frac{\mathrm{x}}{\sqrt{4\left(\mathrm{t}-\mathrm{t_{ex}}\right)\mathrm{D_a}}} \tag{1}$$

where C (x, t) is the chloride concentration at a distance x from the surface at time t; C_i is the initial chloride concentration; C_{sa} is the surface chloride concentration; x the depth of penetration; t is the time of inspection; t_{ex} is the exposure time; D_a is the chloride diffusion coefficient of the concrete; and erfc is the complementary error function.

However, it should be noted that the application of Fick's 2nd Law is focused on the prediction of service-life of existing concrete structures. Therefore, in order to obtain some input parameters, such as surface chloride concentration and the diffusion coefficient, a preliminary inspection to determine the chloride concentration profile is necessary. The application of this law to predict the service-life of new structures is more complex as the estimation of both the parameters mentioned above is not trivial; it often depends on the previous data of similar structures or, in many cases, requires the results of laboratory tests for obtaining the diffusion coefficient, where the corrosive process is generally accelerated. As already mentioned, the accelerated tests receive several criticisms since some acceleration factors are applied in order to minimize the time to obtain the results, which are characterized for exposure conditions that may not effectively represent the real conditions of exposure of a structure, especially with regard to environmental fluctuations [37].

Andrade, Possan and Dal Molin [38] mentioned that the Fick's 2nd Law has low reliability for the prediction of service-life of new concrete structures, because several parameters are involved in the analysis, and the correlation between these parameters is uncertain.

In addition, for the application of Fick's 2nd Law are considered some simplifications that can influence the accuracy depth of chlorides estimated by the model in question, among which, it is mentioned: (i) it is assumed that the concrete is a homogeneous and isotropic material; (ii) the chloride diffusion coefficient is constant in time and space; (iii) the chloride flux occurs under saturation conditions and the only mechanism of transport is diffusion; (iv) the surface concentration of chlorides is also considered constant over time and space; (v) it is assumed that there is no interaction between the chlorides and the concrete components during penetration [43].

In this context, simultaneously with diffusion, the mechanism of absorption transport may also occur. In addition, there is a strong interaction between the chlorides and the components of the cement matrix, mainly with the tricalcium aluminate (C_3A), forming Friedel's salt ($C_3A{\cdot}CaCl_2{\cdot}10H_2O$). Several studies that investigated the interaction between the chlorides and the constituents of the cement indicate that the higher the C_3A content, the greater the chloride fixing capacity of a cement [44, 45]. In this way, the greater the cement fixing capacity, the lower the amount of free chlorides (form that effectively is detrimental to the disassembling of the reinforcement and the durability of the reinforced concrete structures). Another inconsistency regarding the simplifications mentioned above concerns the fact that only in the submerged parts of concrete structures the saturation condition occurs, unlike that observed in marine atmosphere and tidal zones [46].

Most models available for the prediction of service-life, that consider the initiation of corrosion by chlorides are complex, and aim to model the phenomena of degradation with fidelity. Therefore, they require previous data of similar structures or input parameters that are usually obtained from laboratory tests in which more specific characteristics of the concrete are evaluated, thereby limiting the practical application of these models. Equation 2, proposed by Tang and Nilsson [30] is mentioned as an example, which considers the effects of the chemical and physical fixations of the chlorides inside the concrete:

$$\frac{\partial \mathrm{c}}{\partial \mathrm{t}} = \frac{1}{1+\mathrm{ABc}^{\mathrm{B}-1}}\left[\frac{\partial \mathrm{D}(\mathrm{x},\mathrm{t})}{\partial \mathrm{x}}\frac{\partial \mathrm{c}}{\partial \mathrm{x}} + \mathrm{D}(\mathrm{x},\mathrm{t})\frac{\partial^2 \mathrm{c}}{\partial \mathrm{x}^2}\right] \tag{2}$$

where C is the free chloride concentration in the concrete pores at depth x; A is a constant calculated through Eq. 3; B is the adsorption constant, function of the cement type, and the ion involved in transport; and D (x, t) is the variation of the diffusion coefficient in time (Eq. 4).

$$\mathrm{A} = \frac{\left(1+\mathrm{W_n^0}\right)\propto}{\frac{1}{\mathrm{f_c}}+\mathrm{W_n^0}\propto}\,\frac{\mathrm{f_a}}{\mathrm{V_p}} \tag{3}$$

where W_n^0 is the non-evaporable water fraction = 0.25; ∝ is the hydration degree; f_a is the adsorption constant, function of the cement type, and the ion involved in transport; f_c is the cement content in concrete; and V_p is the pore volume per unit mass of the dried sample.

$$D(x,\ t) = \frac{D_0}{\varepsilon_p} f(x) g(t) e^{\frac{E}{R}\left(\frac{1}{T_0} - \frac{1}{T}\right)} \tag{4}$$

where D_0 is the diffusion coefficient of the hydrated concrete; ε_p is the porosity of the matrix of a concrete sample, defined by Eq. 5; f (x) is the function related to depth variation; g (t) is the function related to age of the material; E is the activation energy of the diffusion process; R is the Boltzman constant for gases; T is the temperature of concrete; and T_0 is the temperature at the time of determination of D_0.

$$\varepsilon_p = \frac{\left(\frac{1}{f_c} + W_n^0 \propto\right) V_p}{\frac{(1-\propto)}{\gamma_{cement}} + \frac{(1+W_n^0)\propto}{\gamma_{gel}} + \left(\frac{1}{f_c} + W_n^0 \propto\right) V_p} \tag{5}$$

where γ_{cement} is the specific mass of the Portland cement and γ_{gel} is the specific mass of the gel.

When proposing a new methodology for predicting the service-life (Fig. 1), for selecting the degradation model to be used, Possan et al. [39] indicate that mathematical modeling results in empirical or complex models. The authors cite that the empirical models are easier to apply, but present simplifications, which could generate results with low accuracy. Although the complex models consider a greater number of factors that influence the process of degradation and are more difficult to apply, they provide a greater precision and generalization. The authors indicate that the selection of a service-life prediction model should be based on the desired response and should consider the limitations associated with mathematical models.

In this context, the formulation proposed by Andrade [37–39] is advantageous as it is a mathematical model with high practical applicability and easy understanding, that aims to describe the chloride penetration in concrete structures over time. This model was obtained by a focused group experiment conducted with specialists in the area of durability of structures and materials technology and which involves input variables that are easy to obtain and are already usual in projects, which are understood by all engineers and designers, such as w/c ratio, compressive strength after 28 days, cement type, among others.

The validation of the Andrade's model [37–39] for the greatest number of possible combinations is fundamental, since it will contribute to the consolidation of a tool of simple application for the modeling of the ingress of chlorides into the concrete and, consequently, will help engineers and designers to ensure the project life required by Brazilian regulations [10]. It will also allow the evaluation of the influence of the various design parameters on the service life of these structures, such as cement type, w/c ratio and concrete compressive strength. Finally, it will help in calculating the remaining life time of concrete structures, enabling interventions and preventive maintenance to ensure the durability of such structures.

The input data parameters of Andrade's model, associated with the concrete characteristics and environmental conditions, are determined from Eq. 6. The aim of this research is to evaluate the performance of the mathematical model proposed by Andrade [37–39] in predicting the chloride penetration into structures in marine environments.

$$y = 7.35.\frac{UR^{0.7}.T^{0.1}.Cl^{0.7}}{K_1.f_{ck}.K_2.(1 + Ad)^{0.2}}.\sqrt{t} \tag{6}$$

where y is the position of the chloride ion penetration front, equivalent to a chloride content of 0.4% in relation to the mass of cement (mm); UR is the relative humidity of atmosphere (%); T is the ambient temperature (°C); Cl is the surface chloride concentration, corresponding to the present chloride content by the end of first year of exposure (%); K_1 is a factor that varies according to the cement type used in concrete production (Table 1); f_{ck} is the compressive strength of concrete at 28 days (MPa); K_2 is a factor that varies according to the admixture type used in concrete production (Table 2); Ad is the admixture content in the concrete (%); and t is the exposure time (years).

3 Application

In order to evaluate the application of Andrade's model [37–39] for the largest possible number of combinations, the existing literature was reviewed to find studies related to the chloride penetration in concrete structures located in marine environments. In addition to chloride penetration profiles, the data should contain the following information, that are necessary for the application of Andrade's model: relative humidity of the environment, temperature, surface chloride concentration, cement type, compressive strength at 28 days, type and percentage of the admixture, and exposure time.

After the required experimental data are obtained from the literature, they were compared with the penetration depth of critical chloride concentration calculated by Andrade's model [37–39], based on which, the model was evaluated. It is important to note that as there were no previous environmental data on chloride concentration in structures located in marine regions, the surface concentration of the experimental data was used as the input parameter in Andrade's model. This parameter was obtained by altering the chloride profile from the equation of the Fick's 2nd Law through a non-linear regression in conjunction with the least squares method.

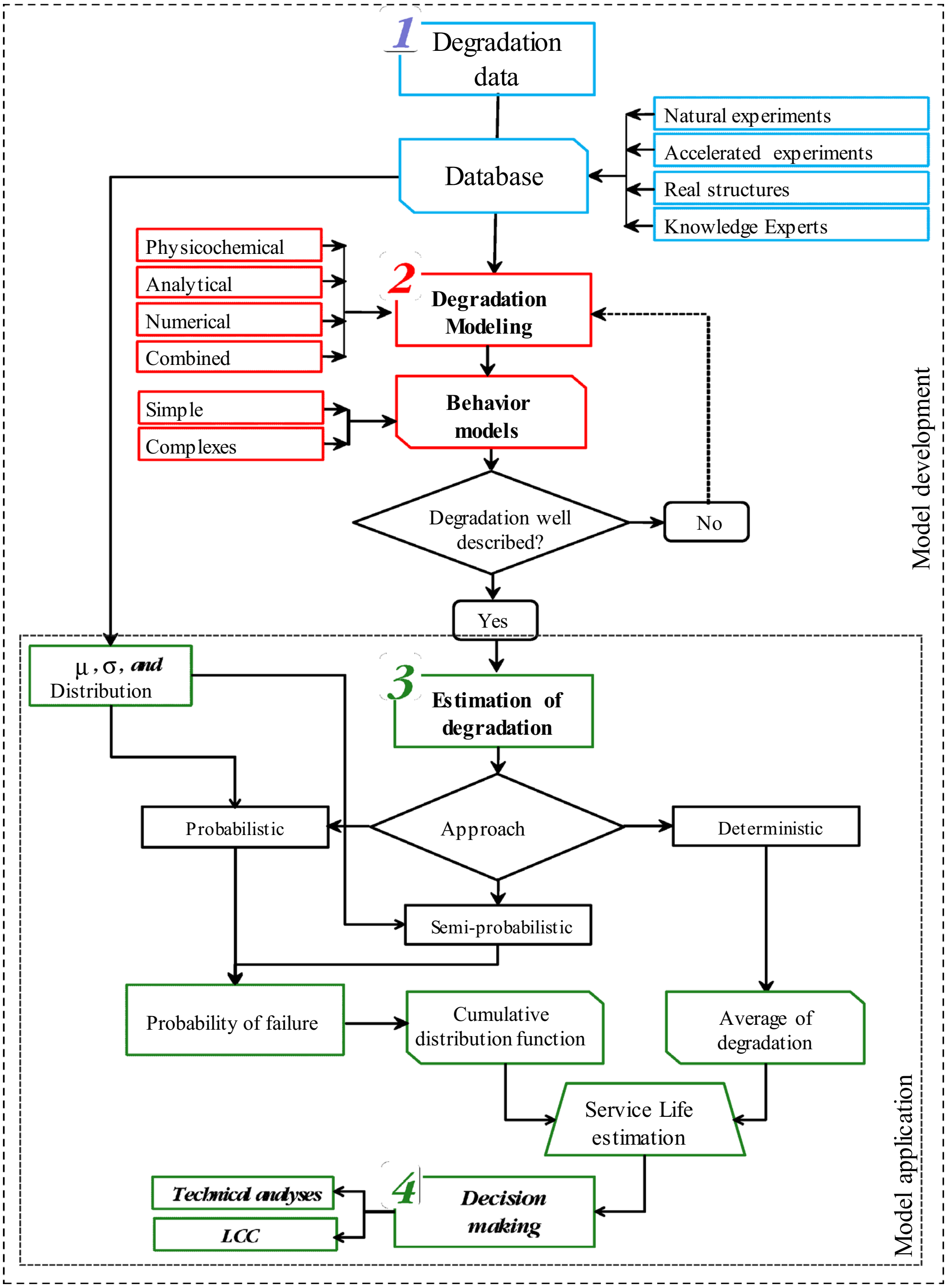

Fig. 1 Flowchart for service-life prediction of reinforced concrete structures. *Source*: Possan, Dal Molin, and Andrade [39]

Table 1 Values of K_1 in function of cement type. *Source*: Andrade [37]

K_1	ASTM cement type
0.98	I (SM)
1.05	I (PM)
1.21	IS
1.17	IP
0.95	III

Table 2 Values of K_2 in function of admixture type. *Source*: Andrade [37]

K_2	Type of admixture
1.00	Silica fume (SF)
0.97	Metakaolin
0.76	Rice husk ash (RRA)

Nine papers meeting the requirements of this study were found, which are:

- Costa and Appleton [47, 48]—The authors evaluated the chloride concentration in concrete panels that were exposed for 3 years in a marine region in the Peninsula of Setúbal, Portugal. Chloride profiles were determined for exposure times of 1.5 and 3 years;

- Coast and Appleton [49]—The authors presented the chloride concentration in a slab of a 35-year-old bridge located in Portugal;
- Pereira [50] and Brito [51]—The authors determined the chloride concentration profile of an offshore platform located in Brazil, about 12 km off the coast of Rio Grande do Norte. Pereira (2003) evaluated a chloride concentration profile corresponding to an exposure time of 24 years and Brito (2008) evaluated a chloride concentration profile with an exposure time of 29 years;
- Meira [52]—The author exposed reinforced concrete blocks in João Pessoa, Paraíba, at a distance of 10 m from the sea. These prisms were molded with OPC and IP cement and w/c ratios of 0.50, 0.57, and 0.65. The chloride concentration was evaluated for the periods corresponding to an exposure time of 0.5, 0.8, 1.2, and 1.5 years;
- Vitali [53]—Concrete prisms were exposed in San Francisco do Sul-Santa Catarina, at a distance of 50 m from the sea. The concrete used in the production of the prisms was composed of IP cement and characterized by a w/c ratio of 0.57, and a compressive strength of 35.2 MPa at 28 days. The chloride concentration profiles of these prisms were determined for the exposure times of 0.5, 0.75, and 1.5 years;
- Boubitsas et al. [54] evaluated the chloride profiles of concretes that remained in a marine region for a period of 20 years in Traslovslage, Sweden. The concretes were cast with Portland cement and w/c ratios of 0.35 and 0.4, and Portland cement + 5% silica fume and w/c ratios of 0.4 and 0.5;
- Wu et al. [55]—The authors determined the chloride profile of the Fangcheng and Qinzhou ports located in the Gulf of Beibu in China with the ages of 80 and 62 months, respectively.

After a preliminary analysis of the data obtained from these studies, it was necessary to define the selection criteria to determine the study to be used. These criteria were established such that the selected model uses precise data for the evaluation of Andrade's model and is in accordance with the physical phenomena of chloride penetration in concrete structures. The first criterion was that the chloride profiles should be composed of at least 5 points as profiles with fewer points do not adequately describe the chloride concentration along the concrete depth. In addition, as mentioned previously, the input parameter "chloride surface concentration" was obtained by altering the profile of the experimental data based on the Fick's 2nd Law. Profiles consisting of fewer points compromise the quality of this alteration, and consequently the value of surface concentration obtained. Considering this factor, as well as that this input parameter is the most significant in Andrade's model (indicated in the sensitivity analysis performed by the author [37]), works containing profiles of chlorides composed of less than 5 points were excluded. Subsequently, the second criterion was that the profiles that present increasing chloride surface concentration and decreasing diffusion coefficient with time be used, conforming to the general behavior expected from these parameters [56]. Considering these two criteria, the studies by Vitali [53], Pereira [50], and Brito [51] were excluded.

To demonstrate the application of Andrade's model [37–39], the data obtained by Meira [52] for concrete produced with IP cement and w/c ratio of 0.65 is presented as an example. Figure 2 shows the chloride profile of this concrete with an exposure time of 0.8 year with the alteration of the experimental data based on the Fick's 2nd Law. By alteration, a surface chloride concentration of 1.075% in relation to cement mass and diffusion coefficient of 73.560 mm^2/year was obtained.

To obtain the surface chloride concentration after the first year of exposure, a input parameter of Andrade's model [37–39], was applied Eq. 7, proposed by Uji et al. [29]. From Eq. 7, it is inferred that in the first year of exposure, the chloride absorption parameter is equal to the surface chloride concentration. Thus, for the data obtained by Meira [52] for concrete produced with IP cement and w/c ratio of 0.65, the surface concentration after the first year of exposure is 1.203% of cement mass.

$$C_s = k_{CS} x \sqrt{t} \tag{7}$$

where C_s is the surface chloride concentration (% cement mass); k_{CS} is the chloride absorption parameter (% cement

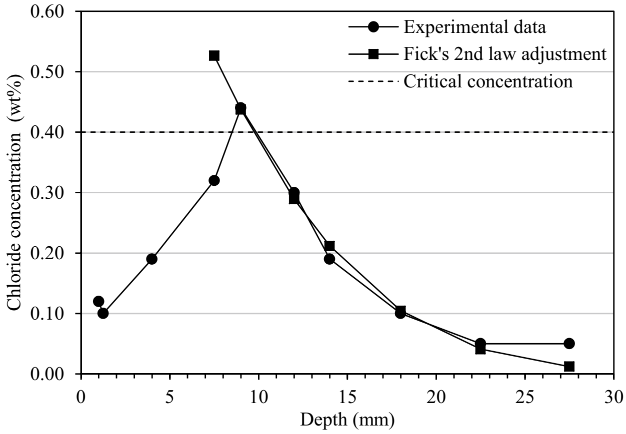

Fig. 2 Chloride profiles of concretes by Meira [52] with IP cement and w/c = 0.65. *Source*: Meira [52], elaborated by the authors

mass/$\sqrt{year}$), depending on the material and exposure zone; and t is the time (years).

After obtaining the surface chloride concentration, Andrade's model [37–39] is applied. In Table 3, all the input parameters for the concrete molded by Meira [52] with IP cement and w/c = 0.65 are presented. Finally, the calculated and measured depth are compared, and the error associated with the values provided by the model is calculated.

Table 3 lists all the data used to evaluate the model. The measured depths of critical chloride concentration, the depths calculated using Andrade's model [37–39], the differences between the measured and calculated values, and the errors associated with the evaluated model are given. In addition, the critical concentration depth was estimated by the Fick's 2nd Law for comparison.

From Table 4, it is verified that the Fick's 2nd Law adequately describes the behavior of critical chloride concentration (adopted as 0.4% of chlorides in relation to the mass of cement). In most cases, the errors associated with the model are low, and the largest percentage error is 20.6%, corresponding to only a difference of 1.4 mm between measured and calculated values. It can be said that the variation in the Fick's 2nd Law is below 10%, which is acceptable. This variation can be partly attributed to the simplifications of the solution by the model, that consider the superficial chloride concentration and diffusion coefficient constant over time.

It was found that Andrade's model provides a good estimation of the depth of critical chloride concentration, mainly due to the small amount of input data and the ease of obtaining them. The differences between the measured and calculated values from the data of Meira [52] are within an acceptable range of variation, presenting the largest error percentage of 34.5%, corresponding only to a maximum difference of 4.6 mm. In this context, Andrade [37] applied his model to four points of a port located in the city of Rio Grande in the southern region of the state of Rio Grande do Sul, with 22 years of exposure. The magnitude of the variations between real data and calculated values established by the author is in the range of −6.3% to 36.8%, similar to the variations found for the previously mentioned data. However, from Table 4, it can be seen that the differences found for some data are larger and will be discussed below.

Table 3 Application of Andrade's model for concrete molded by Meira [52] with IP cement and w/c = 0.65, exposed in marine atmosphere zone for 0.8 year. *Source*: Meira [52], elaborated by the authors

Input parameters—Andrade's model	
Relative humidity (%)	78.3
Mean temperature (°C)	26.5
Environmental chloride concentration—1 year (%)	1.203
K_1	1.17
Compressive strength at 28 days (MPa)	21
K_2	–
Admixture content (%)	–
Time (years)	0.8
Calculated depth (mm)	8.9

Initially, it is important to highlight that variations between calculated and measured values are expected, and can be attributed to the factors such as, the inherent variability associated with the concrete characteristics, environmental conditions, sample extraction process, analysis of results, and the influence of constructive practices. In relation to these variations, it is assumed that the chloride penetration occurs uniformly over the entire surface of the concrete. However, because it is a heterogeneous material, there are variations in the penetration of ions as a function of the analyzed region. In addition, the environmental characteristics considered in Andrade's model [37–39] are in average terms, and the sample extraction process does not have a high precision, mainly as a function of depth ranges, generally between 2 and 5 mm.

In this context, the Brazilian standard NBR 6118 [39] establishes minimum cover for the structural elements, according to the environmental aggressiveness class. Considering the variability of cover thickness, this standard defines that the minimum cover is composed of a nominal value including a tolerance limit of 10 mm, in order to encompass these variations and different levels of execution quality controls. The Brazilian standard NBR 6118 [39] further establishes that in construction, where an adequate quality control and strict limits of variability tolerance are present, or when concrete with resistance classes above the minimum required in this document are used, the tolerance limit may be reduced to 5 mm. Therefore, it is plausible to adopt a similar tolerance limit for the estimations provided by the predictive models of service-life. These variations do not occur ideally; however, due to the low quality control and the construction sector lacking precision, they should be considered. From Table 4, it can be clearly seen that most of the differences between measured and calculated values are within this tolerance limit of 5 mm.

Categorizing the data of Table 4 into two groups as those with errors of less than 35% and those with errors greater than 35%, it is noticed that the first group consists of concretes with small exposure times, whereas the second group consists those with higher exposure times. This indicates that Andrade's model can't be utilized for lower ages, and an alteration is needed for application in the case of longer exposure times. The errors arising when the model is applied to data with higher exposure times are higher, because the input parameter of the model is the surface concentration after the first year of exposure. This indicates that the model needs an alteration in order to make it better evaluate the

Table 4 Depth of critical chloride concentration measured and calculated by Andrade's model [37–39] and Fick's 2nd law

References	Concrete characteristics	Exposure time (years)	Depth measured CCr (mm)	Andrade's Model [27]			Fick's 2nd Law		
				Depth Ccr (mm)	Deviation (mm)	Error (%)	Depth Ccr (mm)	Deviation (mm)	Error (%)
Meira [33]	IP cement w/c = 0.5	0.8	4.0	4.0	0.0	−0.9	4.1	−0.1	−1.5
		1.2	6.0	4.9	1.1	17.6	5.0	1.0	17.1
		1.5	7.0	5.5	1.5	21.1	5.6	1.4	20.6
Meira [33]	IP cement w/c = 0.57	0.8	7.5	5.7	1.8	23.7	6.9	0.6	8.3
		1.2	8.5	7.0	1.5	17.5	8.4	0.1	0.9
		1.5	9.5	7.8	1.7	17.5	9.4	0.1	0.9
Meira [33]	IP cement w/c = 0.65	0.8	10.0	8.9	1.1	10.6	9.7	0.3	3.1
		1.2	11.5	11.0	0.5	4.8	11.9	−0.4	−3.2
		1.5	13.0	12.2	0.8	5.8	13.3	−0.3	−2.0
Meira [33]	OPC w/c = 0.5	1.5	4.0	4.8	−0.8	−19.7	3.9	0.1	1.7
Meira [33]	OPC w/c = 0.57	1.5	9.0	8.4	0.6	6.7	8.7	0.3	2.9
Meira [33]	OPC w/c = 0.65	0.8	9.0	9.2	−0.2	−1.9	8.7	0.3	2.9
		1.2	10.8	11.2	−0.4	−4.0	10.7	0.1	0.9
		1.5	12.6	12.6	0.0	0.3	12.0	0.6	5.0
Costa and Appleton [30]	OPC fck = 34 MPa	1.5	20.8	12.3	8.5	40.9	20.9	−0.1	−0.5
		3	30.0	17.4	12.6	42.0	29.6	0.4	1.5
Costa and Appleton [30]	OPC w/c = 0.32	35	21.0	10.3	10.7	50.8	22.0	−1.0	−4.8
Boubitsas, Luping and Utgennat [21]	OPC w/c = 0.4	20	33.8	15.9	17.9	52.8	35.1	−1.3	−4.0
Boubitsas, Luping and Utgennat [21]	OPC w/c = 0.35	20	25.9	9.6	16.3	62.8	26.4	−0.5	−1.8
Boubitsas, Luping and Utgennat [21]	OPC + 5% SF w/c = 0.4	20	18.8	8.4	10.4	55.4	19.1	−0.3	−1.9
Boubitsas, Luping and Utgennat [21]	OPC + 5% SF w/c = 0.5	20	43.5	11.0	32.5	74.7	43.1	0.4	1.0
Wu, Li and Yu [35]	OPC − w/c = 0.4 (Fangcheng)	6.7	13.7	6.1	7.6	55.3	12.7	1.0	7.0
Wu, Li and Yu [35]	OPC − w/c = 0.4 (Qinzhou)	5.2	3.6	4.2	−0.6	−15.6	3.7	−0.1	−3.3

growth of surface chloride concentration over time as this parameter is the most significant in the estimation provided by Andrade's model, as indicated in the sensitivity analysis performed by the author [37].

The chloride surface concentration (*Cs*) in an reinforced concrete element has correlation with several factors related to concrete and the environment, such as: marine aerosol concentration, temperature, consumption and cement type fixing capacity, w/c ratio, humidity, structure direction, among others [57]. As shown by several authors, it is a parameter that tends to grow over time and, after significantly longer periods, presents a stabilization [47, 58]. Tang [58] followed the chloride penetration in concretes exposed in marine environment for a period of 10 years. The results indicated that the chloride surface concentration gradually increased in the first 5 years of exposure and after that remained practically unchanged. The author believes that this increase is a function of the increase in the bonding capacity of the chlorides and in the saturation degree of the air in the pores of the concrete. However, Song et al. [59], after evaluating several publications in the literature on the subject, found that the chloride surface concentration data do not provide a clear relation with the exposure time.

In this way, it is evident the need of correction of the model with regard to the consideration of the growth of the chloride surface concentration over time, since the model, in general, generated depths associated with the critical concentration of chlorides lower than those actually observed.

In addition, the model consists of a deterministic approach, so that the variability inherent in the degradation process is not considered. This type of model is characterized by input variables that are considered in average terms, as well as the response provided. However, due to the inherent variability of concrete characteristics and exposure conditions, for a more realistic service life prediction, the ideal is to use models that present a probabilistic approach.

Therefore, it is suggested that the model proposed by Andrade undergoes modifications, mainly in relation to two fundamental aspects, (i) adopt the growth of the chloride surface concentration over time and (ii) consider the variability of the concrete characteristics and exposure conditions through a probabilistic approach.

It is noteworthy that, unlike the data of others presented in Table 4, the data from Costa and Appleton [49] and Wu et al. [55] are data of real structures, which are often constructed with lower technological accuracy. This information well justifies the greater variation in the concrete properties of these structures obtained by Andrade's model [37–39], resulting in larger differences between observed and estimated values.

4 Concluding remarks

From the evaluation of Andrade's model [37–39] to predict the service-life of reinforced concrete structures located in chloride-environments such as marine regions, we conclude that:

- by comparison of results provided by the model with the experimental data, it was confirmed that the model presents similar values of chloride penetration measured in situ, for the data with small exposure times;
- the error associated with the model for the data with higher exposure times was significant, which indicates that an alteration is needed in order to best evaluate the growth of surface chloride concentration over time;
- finally, for the data evaluated in this study, the model was reliable, with an error range of 35%, with differences of only 4.6 mm between measured and calculated depths of the critical chloride concentration;
- Andrade's model, in general, provides a good estimation of the depth of critical chloride concentration, mainly due to the small amount of input data and the ease of obtaining them. In comparison with the solution of Fick's 2nd Law, it presents as main advantage the non-use of the diffusion coefficient as input parameter, since it usually demands the realization of a preliminary inspection to determine the chloride concentration profile of existing concrete structures and, in the case of new structures, depends on the previous data of similar structures or, in many cases, requires the results of laboratory tests for obtaining the diffusion coefficient, where the corrosive process is generally accelerated, although such exposure conditions not effectively represent the real conditions of exposure of a structure in a marine atmosphere zone, especially with regard to environmental fluctuations;
- it is suggested that the model undergoes modifications, mainly in relation to two fundamental aspects: (i) adopt the growth of the chloride surface concentration over time and (ii) consider the variability of the concrete characteristics and exposure conditions through a probabilistic approach.

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