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Computational modeling for predicting corrosion initiation in reinforced concrete structures

Modelagem computacional para predição do período de iniciação da corrosão em estruturas de concreto armado

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Abstract

This article presents a model for penetration of chloride by diffusion in reinforced concrete structures based on the solution of the Fick's 2nd Law, using the finite element method (FEM) in two-dimensional domain. This model predicts the time, in a given situation, so that a certain limit of chlorides for depassivation of reinforcement is reached, characterizing the end of service life. Several approaches for the chloride surface concentration and for the diffusion coefficient are used, parameter which must be corrected due to the effects of temperature, solar radiation, exposure time, and relative humidity. Moreover, a parametric analysis is carried out in order to study the factors involved and their impact on the ingress of chlorides by diffusion, contributing to a better understanding of the phenomenon. In addition, the developed model is applied to the cities of Vitória (ES) and Florianópolis (SC) to analyze the service life for different concrete covers, making a comparison with the Brazilian standard.

Keywords: chlorides, corrosion, diffusion, finite element method, service life.

Resumo

Este trabalho apresenta um modelo de penetração de cloretos por difusão em estruturas de concreto armado baseado na solução da 2ª Lei de Fick, utilizando o método dos elementos finitos (MEF) no domínio bidimensional. Este modelo prevê o tempo necessário, em determinada situação, para que um determinado limite de cloretos para a despassivação da armadura seja atingido, caracterizando o fim da vida útil. Utilizam-se diversas abordagens para a concentração superficial de cloretos e para o coeficiente de difusão, parâmetro que deve ser corrigido devido aos efeitos da temperatura, da radiação solar, do tempo de exposição e da umidade relativa. Além do mais, é realizada análise paramétrica visando o estudo dos fatores intervenientes e seus impactos na penetração de cloretos por difusão, de modo a contribuir para uma maior compreensão do fenômeno. Ademais, o modelo desenvolvido é aplicado às cidades de Vitória (ES) e Florianópolis (SC) analisando-se a vida útil para diferentes cobrimentos de concreto, fazendo um paralelo com a norma brasileira.

Palavras-chave: cloretos, corrosão, difusão, método dos elementos finitos, vida útil.

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1. Introduction

The current process of changing the paradigm of society in relation to the physical-ecological system gives strength to the theme of sustainable development and, consequently, the construction industry is strongly affected, making the durability of constructions one of the most discussed subjects. Durable structures impact sustainability in two ways: through conservation of energy, raw materials and natural resources; and the reduction in the amount of waste generated. Not to mention the remarkable economic factor, since it has great influence on the cost of the life cycle.

Several are the degradation factors of the reinforced concrete structures. However, special attention must be paid to the corrosion of the reinforcement, one of the most frequent problems and that generate higher costs of repair. Helene [1] provides an analysis of the economic importance of reinforcement corrosion in the world, with surveys in the United States and Spain on the incidence of pathological manifestations in concrete structures and their impacts. Skainy (1987) *apud* Helene [1] points out that in 1985 the volume of resources handled by civil construction in the United States was $ 300 billion, with repair costs estimated at $ 50 billion per year, about 16% of the total sector. In all the studies presented, corrosion was one of the pathological manifestations of higher incidence and higher repair costs. In Brazil, a similar situation is observed. Dal Molin [2], in a case study in the state of Rio Grande do Sul, points out that, even though the incidence of reinforced corrosion in the buildings studied is about 11% of the total pathological manifestations found, when considering only the serious manifestations, with implications for structural safety, this figure rises to 40%, with the highest incidence among them. Moreover, the author points out that the corrosion of reinforcement demands an immediate recovery and is usually expensive, since its permanence may represent a risk to the stability of the building.

Corrosion in reinforced concrete structures is an electrochemical process that requires the presence of an electrolyte, a potential difference, and oxygen. However, the corrosion process will only begin once the reinforcement has been removed, that is, when the thin layer of oxides surrounding the reinforcement is broken [3]. The depassivation of the reinforcement occurs mainly due to two mechanisms: carbonation and chloride action. Although carbonation corrosion occurs in a generalized way, the damage associated with it is usually manifested in the form of cracking and displacement of the cover before a significant reduction in the section of the bar has occurred. In the case of chloride action, an extreme loss of the sectional area of the reinforcement can be reached before any other form of deterioration can be detected. This is the most studied mechanism of corrosion and the one that causes greater damages.

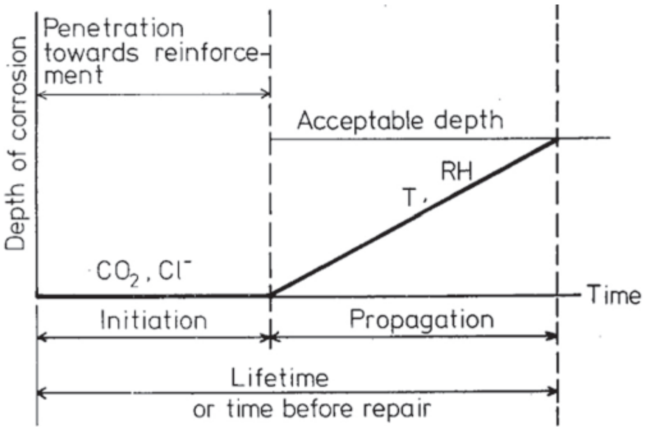


Figure 1
Simplified model for service life associated to corrosion
Source: *adapted from Tuutti [6]*

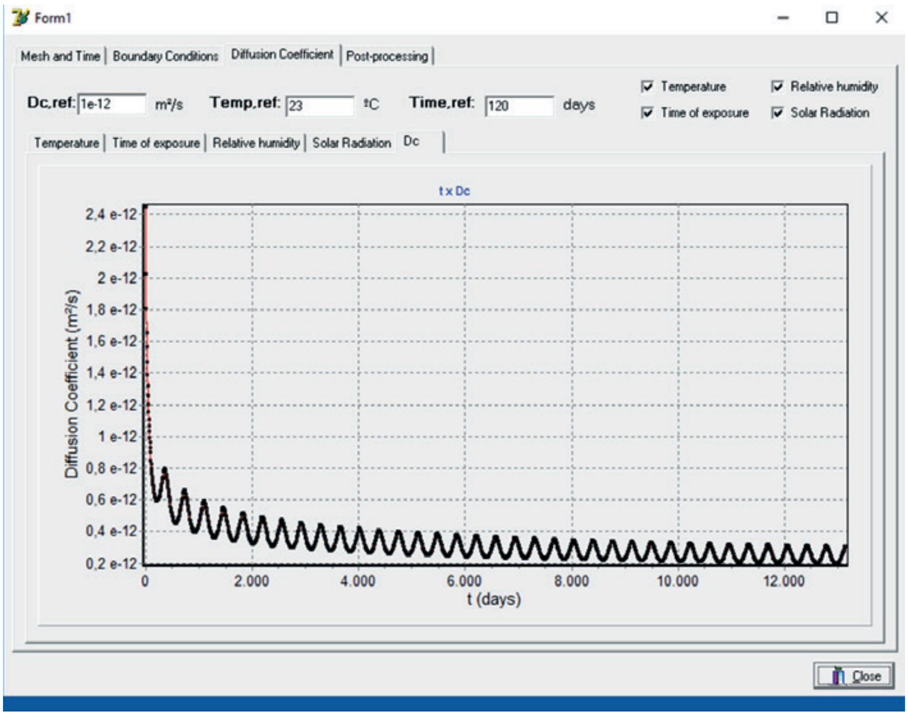
In the corrosion by chloride attack an accumulation of chloride ions occurs in the pore solution in the area of the reinforcement until, upon reaching a critical amount, there is a localized break of the passivating layer [3]. Among the most common sources of chloride contamination in the concrete are contaminated additives or aggregates and the penetration of de-icing salts or seawater solutions through the cover, which acts as a physical protection, making it difficult for external aggressive agents to enter [4].

The durability of the structures is intrinsically linked to the concept of service life. Among the various definitions, stands out the one presented by Andrade [5], who considers service life as “the one during which the structure preserves all the minimal characteristics of functionality, resistance and external aspects required”.

A simplified model for the service life associated with corrosion was proposed by Tuutti [6] and has since been used by practically all the studies. In this study, the corrosion process is divided into two stages (Figure 1). The initiation period, which includes the period of time until the depassivation of the reinforcement, is usually the longest period and, in the case of chloride action, its duration depends on the rate of penetration of chloride ions in the concrete, the depth of the concrete cover and concentration of chlorides. The propagation period is considered as the time between depassivation of the steel rebar, when the corrosion process starts, and the moment when an unacceptable degree of corrosion is reached, marking the end of the service life. This period is considerably shorter and its prediction is rather complex due to the number of intervening factors and the difficulty of obtaining precise input parameters. Thus, it is common to regard the end of the initiation period as the end of service life.

The Brazilian standard NBR 6118 [7] still addresses the durability in a qualitative way, specifying minimum concrete cover and minimum qualities of cover concrete to ensure service life. This standard is based on previous results, not providing information on the service life of structures. However, greater knowledge about the transport mechanisms of liquids, gases and ions in the concrete, makes it possible to associate time with mathematical models that quantitatively express these mechanisms. Thus, deterministic methods allow the evaluation of the service life expressed in number of years and no longer in only qualitative criteria of adequacy of the structure to a certain degree of exposure [8].

Consequently, there is an effort to mathematically model the phenomenon of reinforcement corrosion, allowing the estimation of service life of reinforced concrete structures in order to adequately guide the maintenance activities and to design based on the



Dc,ref: 1e-12 m²/s
Temp,ref: 23 ºC
Time,ref: 120 days
☑ Temperature
☑ Relative humidity
☑ Time of exposure
☑ Solar Radiation

Figure 2
Interface of software developed

durability, not only on the mechanic strength and structural safety. Although it has been a much studied subject since the 70's, there are many gaps in the knowledge of the processes of corrosion of reinforcements. A considerable amount of service life prediction models has already been developed. However, the existence of a large number of intervening factors, the lack of a precise understanding about the physical models that cover these factors and the difficulty in obtaining exact input parameters, of real structures and over long periods, are enormous obstacles found in their modeling [9]. Thus, there is still no widely accepted approach, and these models have not yet been able to effectively reach the market.

Therefore, this study presents a diffusion chloride penetration model in reinforced concrete structures using the finite element method (FEM) in the two-dimensional domain. This model foresees the time required, in a given situation, so that a certain limit of chlorides for the depassivation of the reinforcement is reached. This study will contribute to the understanding of the phenomenon of corrosion in concrete structures, as well as to serve as a basis for the development of increasingly accurate future models for the reproduction of reality. Moreover, a parametric analysis is carried out aiming at the study of the intervening factors and their impacts on the penetration of chlorides by diffusion, in order to contribute to a better understanding of the phenomena involved. Also, the developed model is applied to the city of Vitória (ES) and Florianópolis (SC), using the local climatic parameters to analyze the service life for different concrete covers.

2. Chloride diffusion model

This section provides an overview of the software developed and presents the model used. The program was developed using Object-Pascal (Delphi® 7.0); an object-oriented language in the Windows® environment and it is based on the finite element method (FEM) in the two-dimensional domain. Free external software (GMSH[1]) is used for the generation of meshes. However, all the rest of the procedures are performed by the software program itself, through a user-friendly interface (Figure 2) and data entry windows that allow the manipulation of all parameters considered. The program was developed based on Tavares [10], with the insertion of different models for surface concentration and the implementation of the influence of solar radiation and skin effect.

This study presents a model of penetration of chlorides in structures of reinforced concrete by diffusion based on the solution of Fick's 2nd Law (Equation 1).

$$\frac{\partial C}{\partial t}=\frac{\partial}{\partial x}\left(D\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(D\frac{\partial C}{\partial y}\right) \tag{1}$$

Where C is the concentration of chlorides, t the time, x and y is the spatial coordinates and D is the apparent diffusion coefficient of chlorides.

This model foresees the evolution of the chloride concentration over time, as well as the time required, in a given situation, so that the chloride limit for the depassivation of the reinforcement is reached. Several approaches are used for the superficial concentration of chlorides and

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[1] http://gmsh.info/

for the estimation of the diffusion coefficient, a parameter that must be corrected due to effects of temperature, time of exposure and relative humidity, in order to estimate the service life of the part studied.

2.1 Diffusion coefficient

Several studies show that the assumption suggested by Crank [11], in which the diffusion coefficient is constant, is not correct [12, 13]. This variation in time leads to large implications for long-term predictions of chloride penetration and thus a constant value can lead to serious errors [12]. Thus, the software developed in this study allows, besides the choice of a constant diffusion coefficient, the consideration of the effect of temperature, solar radiation, relative humidity, time of exposure and skin effect.

The diffusion coefficient is determined from a reference coefficient, measured in the laboratory and influenced by several internal parameters, such as concrete mix design, cure and composition of the concrete, multiplied by a series of functions, used to model the influence of cement hydration and of the environment where the concrete is located (Equation 2).

$$\mathrm{D_c} = \mathrm{D_{c,ref}} \, . \, \mathrm{f_1(T)} . \, \mathrm{f_2(t_e)} \, . \, \mathrm{f_3(h)} \tag{2}$$

Where Dc, ref is the reference diffusion coefficient, measured at the specified temperature and time, f1 (T) considers the influence of temperature and solar radiation, f2 (t) of the degree of hydration and f3 (h) of the relative humidity of pores.

2.1.1 Effect of temperature

The effect of temperature on the diffusion coefficient is estimated by the Arrhenius equation (Equation 3), which expresses the variation of a chemical reaction with temperature.

$$\mathrm{f_1(T)} = \exp\left[\frac{\mathrm{U}}{\mathrm{R}}\left(\frac{1}{\mathrm{T_{ref}}} - \frac{1}{\mathrm{T}}\right)\right] \tag{3}$$

Where U is the activation energy of the chlorides diffusion process (kJ/mol), R is the gas constant (kJ/K mol), Tref is the reference temperature at which the diffusion coefficient was measured (K), and T is the temperature in the concrete (K). The thermal sensitivity of a reaction is indicated by the activation energy, which is the amount of energy required for a reaction to occur. Page *et al*. [14] suggests values for diffusion activation energy in cement pastes of (41.8 + - 4.0) kJ / mol, (44.6 + - 4.3) kJ / mol and (32.0 + - 2.4) kJ / mol for water/cement ratios of 0.4, 0.5 and 0.6, respectively.

In order to mathematically model the temperature variation in the concrete, the developed software uses a sinusoidal function. Equation 4, defined from the annual maximum temperature (T_{max}), the annual minimum temperature (T_{min}) and the day on which the highest temperature occurs (day_{max}), determines the temperature (T) for a given day of the year (t).

$$T = \frac{T_{min} + T_{max}}{2} + \frac{T_{max} - T_{min}}{2} \times \sin\left(\frac{t}{365} \times 2\pi + \left(0{,}5 - \frac{2 \times day_{máx}}{365}\right) \times \pi\right) \tag{4}$$

2.1.2 Effect of solar radiation

The radiation emitted by the sun and incident in the Earth's atmosphere causes an increase in temperature in the structures. This variation has a direct influence on the diffusion coefficient of chlorides. Despite this influence, this is still a subject little addressed and its consideration is an innovation presented in this model. The solar radiation is considered in the multiplicative function f1 (T) (Equation 3) from an increase in the external temperature.

In the absence of specific measurements of solar radiation for a given location, the data present in the Solarimetric Atlas of Brazil can be used [15]. These data refer to the daily global solar radiation on a monthly average received by a horizontal surface for each month. According to the available data, the total daily solar radiation on a sloping surface is obtained from the global radiation on a horizontal surface. To do this, one must know the direct and diffuse components of the radiation on the horizontal surface. The direct radiation is the one received from the sun without being dispersed by the atmosphere and the diffuse radiation is the one received from the sun after its direction has been altered by the atmosphere [16].

The method proposed by Liu and Jordan (1963, 1967) *apud* Agullo [17], allows estimating the daily diffuse radiation, H_d, from the daily global radiation on monthly average, H_0, according to Equation 5.

$$H_d = H_o . \left(1{,}39 - 4{,}027K_T + 5{,}531K_T^2 - 3{,}108K_T^3\right) \tag{5}$$

Where, K_T is the average monthly cloudiness index, defined by the ratio between daily global radiation, monthly average, H_0 and solar extraterrestrial radiation, monthly average, H_e (Equation 7). The method for obtaining the daily solar radiation on a sloped surface presented below is used by Agullo [17] and is also described by Duffie and Beckman [16].

$$K_T = \frac{H_o}{H_e} \tag{6}$$

Extraterrestrial solar radiation can be found by the expression:

$$H_e = \frac{24}{\pi} r^2 . I_{SC} (\cos\delta \cos\phi \sin h_s + h_s \sin\delta \cos\phi) \tag{7}$$

In which:

r²: correction factor of the solar constant for each day of the year (Equation 8);

I_{SC}: solar constant I_{SC} = 4870.8 KJ / hm²;

ϕ: surface latitude;

δ: solar declination;

h_S: module of the hour angle corresponding to the sunset (radians).

$$r^2 = 1 + 0{,}033 \cos\frac{360\,Z}{365} \quad 1 \leq Z \leq 265 \tag{8}$$

The time angle and the declination are the coordinates that define the position of the sun with respect to a point P on the Earth's surface (Figure 3). According to Duffie and Beckman [16]: the latitude is the angular location to the north or south of the equator, being null at the equator, + 90 ° in the north pole, and -90 ° in the south pole; The solar declination (δ) is the angular position of the noon

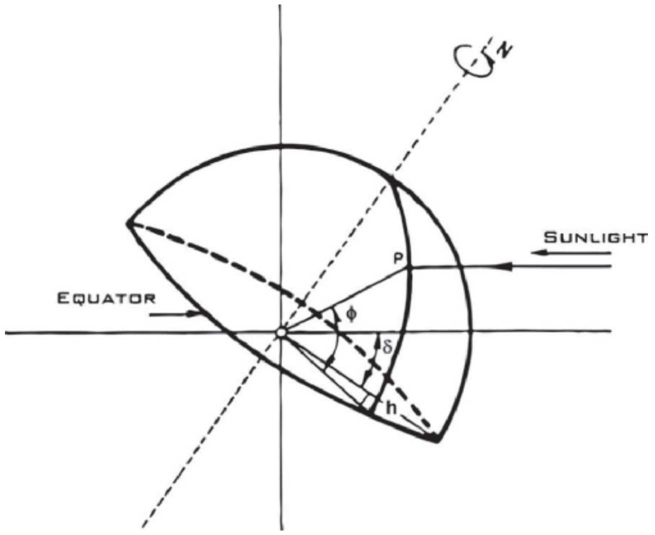

Figure 3
Latitude, hour angle, solar declination
Source: *adapted from Agullo[16]*

sun in relation to the plane of the equator, positive north (-23.45° ≤ δ ≤ 23.45 °); The time angle (h) is the angular displacement of the sun to the east or west of the local meridian due to the rotation of the Earth on its axis at 15° per hour (360° in 24 hours) - being zero when the sun passes through the meridian of the point (solar noon), positive in the afternoon and negative in the morning. The declination can be found by Equation 9:

$$\delta = \frac{180}{\pi}\begin{pmatrix} 0{,}006918 - 0{,}399912\cos B + 0{,}070257\sin B - \\ 0{,}006758\cos 2B + 0{,}000907\sin 2B - \\ 0{,}002697\cos 3B + 0{,}00148\sin 3B \end{pmatrix} \quad (9)$$

Where B is given by:

$$B = \frac{360}{365}(n-1) \quad (10)$$

Being n the n^{th} day of the year.
The time angle corresponding to the sunset can be obtained by Equation 11:

$$h_s = -\tan\phi\tan\delta \quad (11)$$

Thus, the diffuse radiation component (H_d) is defined.
The direct component of the radiation, H_b, is obtained by the difference between the daily global radiation and its diffuse component (Equation 12).

$$H_b = H_0 - H_d \quad (12)$$

After calculating the diffuse and direct components of the daily global, monthly average radiation on a horizontal surface, one can obtain the hourly radiations in the interval between sunrise and sunset in the studied location. To do so, one must know the duration of the solar day, defined in relation to the true solar time (TSV). TSV is the time based on the apparent angular movement of the sun, with solar noon when the sun crosses the meridian of the observer, which does not coincide with local time [16].

The start time and the end time of the solar day are defined by Equation 13 and Equation 14, respectively [17].

$$TSV_i = 12 - \frac{1}{15}\cos^{-1}(-\tan\phi\tan\delta) \quad (13)$$

$$TSV_f = 12 + \frac{1}{15}\cos^{-1}(-\tan\phi\tan\delta) \quad (14)$$

Thus, the global and diffuse hourly radiations for each hour of the solar day can be obtained, respectively, by Equations 15 and 16,

$$H_{h,0} = r_t \,.\, H_0 \quad (15)$$

$$H_{h,d} = r_d \,.\, H_d \quad (16)$$

In which the factors r_t and r_d, defined as a function of the hour angle, are determined from Equations 17 and 18, respectively.

$$r_d = \frac{\pi}{24} \,.\, \frac{\cos h - \cos h_s}{\sin h_s - h_s\cos h_s} \quad (17)$$

$$r_t = \frac{\pi}{24} \,.\, (a + b\cos h) \,.\, \frac{\cos h - \cos h_s}{\sin h_s - h_s\cos h_s} \quad (18)$$

Where h is the hour angle, obtained by:

$$h = (TSV - 12) \,.\, 15 \quad (19)$$

$$a = 0{,}4090 + 0{,}5016\sin(h_s - 60) \quad (20)$$

$$b = 0{,}6609 + 0{,}4767\sin(h_s - 60) \quad (21)$$

Direct hourly radiation is found by the difference between the global hourly radiation and the diffuse hourly radiation.

$$H_{h,b} = H_{h,0} - H_{h,d} \quad (22)$$

Once the direct and diffuse hourly components of the solar radiation on a horizontal surface are obtained, the radiation incident on a sloped surface can be determined. The direct component on a sloped surface can be expressed by Equation 23.

$$I_{h,b} = R_b \,.\, H_{h,b} \quad (23)$$

Where the factor R_b is given by the ratio between the cosine of the angle of incidence of the solar rays (θ) and the cosine of the zenith (ψ).

$$R_b = \frac{\cos\theta}{\cos\psi} \quad (24)$$

Where S is the angle between the plane of the surface in question and the horizontal:

$$\cos\theta = \sin\delta\sin\phi\cos S - \sin\delta\cos\phi\sin S\cos\gamma + \\ \cos\delta\cos\phi\cos S\cos h + \cos\delta \quad (25)$$

$$\cos\psi = \sin\phi\sin\delta + \cos\phi\cos\delta\cos h \quad (26)$$

According to Duffie and Beckman [16]: the angle of incidence of solar rays (θ) is the angle between the direct radiation on a surface and the normal one to that surface; The zenith (ψ) is the angle between the vertical and a line to the sun; The surface azimuth (γ) is the deviation of the projection, on horizontal plane, from the normal

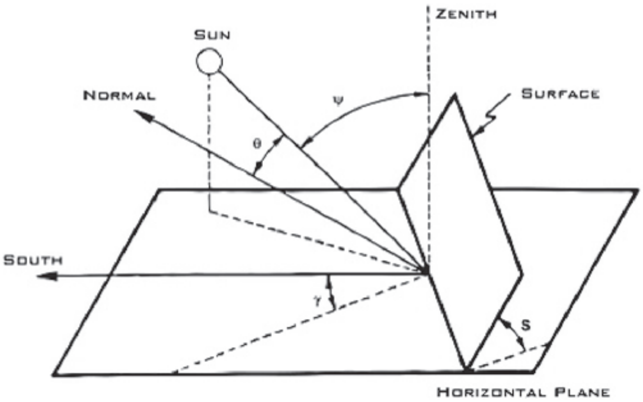

Figure 4
Incidence of sunlight on sloped surface
Source: *adapted from Agullo [16]*

to the surface, with zero in the south, negative east and positive west (Figure 4).

By using Equation 25, the angle θ can exceed 90°, which means that the sun is behind the surface. Also, it is necessary to ensure that the earth is not blocking the sun, that is, that the hour angle is between sunrise and sunset.

Using the diffused isotropic radiation model proposed by Liu and Jordan (1963) *apud* Duffie and Beckman [16], the radiation on the inclined surface is considered as three components: direct radiation, isotropic diffuse radiation and radiation reflected by the terrain. An inclined surface of angle S with the horizontal has a sky vision factor of $F_C = (1 + \cos S) / 2$. Thus, the diffuse component on the sloped surface is:

$$I_{h,d} = \frac{1 + \cos S}{2} H_{h,d} \qquad (27)$$

The sloped surface has a field view factor of $F_T = (1 - \cos S) / 2$, and if the surroundings have a reflection coefficient ρ, the radiation from the terrain to the surface is:

$$I_{h,r} = \rho \, . \frac{1 - \cos S}{2} \, . \left(H_{h,d} + H_{h,b}\right) \qquad (28)$$

Table 1 shows typical reflection coefficient values.

The total hourly solar radiation incident on the inclined surface will be obtained by the sum of the direct, diffused and reflected hour components (Equation 29).

$$I_h = I_{h,b} + I_{h,d} + I_{h,r} \qquad (29)$$

Finally, the total daily solar radiation on the inclined surface, I_d, is calculated as the sum of the hourly radiations in the interval of hours of sunshine, from sunrise to sunset. According to Stucky and Derron [18], concrete is not a blackbody and thus only part of the energy received by sunshine and other phenomena is absorbed, and it can be considered, for the wavelength zone in question, from 50 to 70% absorption. The authors also state that the effect of this energy received by radiation in the calculation of the temperature of the concrete can be considered as an increase of the external temperature, according to Equation 30.

$$\Delta T = (0{,}50 \; a \; 0{,}70) \frac{I_d [MJ/m^2 day]}{24 \, [h/day] . \, \alpha \, [MJ/m^2 h ºC]} \qquad (30)$$

Where I_d is the total daily solar radiation and α is the transmission coefficient at the air-concrete contact, which may vary depending on the intensity of the convective currents and wind incident on the surface, from 15 to 40 Cal/m²hºC [18].

2.1.3 Effect of exposure time

The continued hydration of the cement leads to a reduction in the porosity of the concrete. Thus, the aging of concrete, depending on the type of cement, leads to a significant drop in the diffusion coefficient over time and, therefore, disregarding this mechanism can lead to very conservative predictions of corrosion time [13]. The dependence over time is considered through Equation 31.

$$f_2(t) = \left(\frac{t_{ref}}{t}\right)^m \qquad (31)$$

Where t_{ref} is the time at which the reference diffusion coefficient (s) was determined, t is the exposure time (s) and m is the ageing factor. Bamforth (1998) *apud* Martín-Pérez [19] proposes values of m of 0.264 for ordinary Portland cement (OPC), 0.699 for concrete with fly ash (FA), and 0.621 for concrete with ground granulated blast-furnace slag (GGBS). It is worth mentioning that, in order to increase the reliability of the predictions, there is a need of further studies, addressing the ageing factor "m" for several types and levels of admixtures.

2.1.4 Effect of humidity

The effect of humidity on the diffusion coefficient is of great importance, since the diffusion process only occurs in the presence of water in the pores. Thus, Saetta *et al.* (1993) *apud* Martín-Pérez [19] proposes that the reduction in diffusity with the loss of humidity can be expressed by Equation 32.

Table 1
Coefficient of reflection of the surroundings

Type of soil	ρ
Recent snow	80-90%
No recent snow	60-70%
Cropping areas:	–
Without vegetation	10-15%
Dry grass	28-32%
Prairie and forests	15-30%
Sandy area	15-25%
Cement, concrete	55%
Light sand	25-40%
Water:	–
Summer	5%
Winter	18%

Source: Coronas *et al.* (1982) *apud* Agullo (1991)

$$f_3(h) = \left[1 + \frac{(1-h)^4}{(1+h_c)^4}\right]^{-1} \quad (32)$$

Where h is the relative humidity in the pores of the concrete and h_c is the humidity in which the diffusion coefficient falls to the intermediate value between its maximum and minimum values, Bazant and Najjar *apud* Martín-Pérez [19] assume this value as 0.75 for the drying concrete.

As in the case of temperature, in order to mathematically model the relative humidity variation in the concrete pores throughout the year, the developed software uses a sinusoidal function (Equation 33), defined from the maximum annual humidity, the annual minimum humidity and of the day when the highest humidity occurs.

$$h = \frac{h_{min} + h_{max}}{2} + \frac{h_{max} - h_{min}}{2} \times \sin\left(\frac{t}{365} \times 2\pi + \left(0{,}5 - \frac{2 \times day_{máx}}{365}\right) \times \pi\right) \quad (33)$$

2.1.5 Skin effect

The concrete “skin” is the area closest to the cover surface. It usually has a different composition from that of the innermost layers due to phenomena such as contact with forms, carbonation, brucite precipitation - the concrete exposed to seawater may have its resistivity increased by the formation of a thin surface layer of brucite ($Mg(OH)_2$) [20] - , segregation of aggregates and even when concrete presents some coating or painting [21]. The existence of a surface layer with a different diffusivity will cause a change in the chloride concentration profiles. Higher skin diffusivity values can occur when the skin is carbonated and when chlorides penetrate through capillary suction. The opposite case, with lower diffusivity, occurs when there is some barrier effect on the surface, such as brucite precipitation or coating paint use [21, 22].

Andrade *et al*. [21] models the skin effect considering different values for the diffusivity of the superficial and inner layer, an approach also used in this study. As the concentration of chlorides in the boundary between the skin and the inner part becomes the surface concentration (boundary condition) of the concrete inner part (Figure 5).

2.2 Boundary conditions

To solve Fick’s equation it is necessary to define the boundary conditions of the problem. It is common to consider null value for the initial concentration of chlorides. However, if there is contamination of the ingredients of the mixture, this value can be specified.

The surface concentration of chlorides is commonly considered as a constant value. However, Costa and Appleton [12] point out that it is variable in time and this approximation can cause great errors for long term predictions. In fact, Andrade *et al*. [23] demonstrate the importance of surface concentration by comparing eight diffusion models. The results indicate that the surface concentration assumes a much more significant role than the diffusion coefficient, a theme that usually attracts a much larger number of studies, which is in line with parametric analyses performed by other authors [24, 25]. The authors conclude by stating that a crucial factor is to have a law of consistent surface concentration evolution. Thus, the developed software allows five different approaches, one of them being the adoption of a constant value. It is also possible to select which surfaces are subject to chloride penetration.

The approach presented by Uji *et al*. [26] proposes an expression for the boundary condition in which the surface concentration tends to increase with the service time of the structure, according to a linear function of the age root of the concrete (Equation 34).

$$C_s = S\sqrt{t} \quad [\%\ concrete\ weight] \quad (34)$$

Where S is a coefficient dependent on the structure type and exposure zone [1/√s] and t is the exposure time [s]. The intervals of values found by the authors for S were (5.31-16.6 x 10-6 1/√s) for the splatter zone, (18.2-23.5 x 10-6 1/√s) for the tidal zone and (1.56-5.57 x 10-6 1/√s) for the atmospheric zone.

In another approach, proposed by Collins and Grace [27], after an initial increase, the surface concentration reaches a limit value, becoming constant (Equation 35). According to the authors, the magnitude of this limit is related to the cement system and to the porosity of the surface layer.

$$C_s = C_s^{ult} \cdot \frac{t}{t + T_{Cs}} \quad [\%\ concrete\ weight] \quad (35)$$

Where $C_{s,ult}$ is the final surface concentration, found by the authors

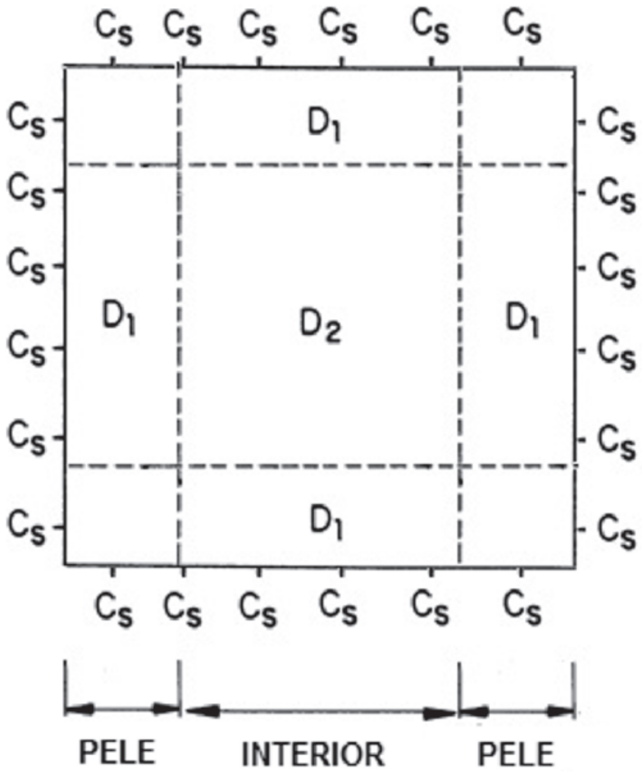

Figure 5
Skin effect
Source: *adapted from Andrade et al. [20]*

Table 2
Summary of the chloride surface concentration models

Authors	Equation	Description
–	$C_S = cte$	Constant during all the structure's service life
Uji *et al.* (1990)	$C_S = S\sqrt{t}$	Increases with exposure time.
Collins e Grace (1997)	$C_S = C_{s,ult} \cdot \frac{t}{t + T_{CS}}$	After initial increase in the first few years, becomes constant
Ann *et al.* (2009)	$C_S = C_0 + k\sqrt{t}$	Shows initial accumulation and increases with exposure time
Song *et al.* (2008)	$C_S = C_0 + \alpha \ln t$	Shows initial accumulation and increases with exposure time

as 0.6% for a ordinary Portland cement concrete with a water cement ratio of 0.4 and cement content of 450 kg/m³, t is the exposure time (days) and T_{cs} is a parameter that regulates the rate of accumulation of chlorides on the concrete surface (days).

As the surface chloride concentration used by the above studies is given in % by weight of concrete, its weight equivalent of cement can be obtained from the cement content in the concrete (kg/m³), according to Equation 36.

$$C_s\,(\%\ cement\ weight) = C_s\,(\%\ concrete\ weight).\,(2300\,/\,cement\ content\,(kg/m^3)\,) \tag{36}$$

Ann *et al*. [28] and Song *et al*. [29] present models that consider an initial accumulation of chlorides on the surface, which then increases with the exposure time, from Equations 37 and 38, respectively.

$$C_S = C_0 + k\sqrt{t}\ [\%\ cement\ weigth] \tag{37}$$

Where k is the constant under a linear accumulation condition, t is the exposure time and C_0 is the initial accumulation of chlorides on the surface.

$$C_S = C_0 + \alpha \ln t\ \ [\%\ cement\ weigth] \tag{38}$$

Where C_{s0} is the surface concentration at a standard time (e.g., 28 days) and α constant parameter to be determined for the data used.

Table 2 presents a summary of the surface chlorite concentration models implemented in the developed software program.

3. Parametric analyses

The chlorides transport phenomenon, according to the proposed model, involves several parameters that characterize the geometry, the material and the environmental conditions. The aim of this study is to evaluate the influence on chloride penetration of: climatic parameters, exposure time, according to the addition used in concrete, and different approaches for the surface concentration of chlorides (boundary conditions). Table 3 shows the control variables related to geometry and time parameters, common to all studies performed. The other variables are presented in each analysis.

It is important to point out that this study does not aim to find exact values for the concentration of chlorides. Instead, the results obtained should be considered in a relative context, demonstrating the level of influence of each parameter in the initiation period of the structure.

3.1 *Influence of climatic parameters on chloride penetration*

i. Temperature and humidity

The cities of Florianópolis (SC, Brazil) and João Pessoa (PB,

Table 3
Parametric analysis: control variables (time and geometry)

Control variables		Value
Geometry	Dimensions	8 cm x 8 cm
	Concrete cover	3 cm
Mesh	Type of elements	Linear triangular
	Size of elements	0.002
	Number of nodes	2141
	Number of elements	4088
Time parameters	Final time (T)	50 years
	Time step (Δ_t)	5 days

Table 4
Parametric analysis: control variables

Control variables		Value
Boundary conditions	Initial concentration (C_0)	0 %
	Chloride surface concentration (C_s)	2 % cement weight
Diffusion coefficient	Reference diffusion coefficient ($D_{c,ref}$)	1x10 - 12 m²/s
	Reference temperature (T_{ref})	23 °C
	Activation Energy (U)	41.8 kJ/mol
	Humidity parameter h_c	0.75

Brazil) were chosen for this analysis because they are two cities of the Brazilian coast and have very different ambient temperature and humidity values. In addition to these cities, Vancouver (BC, Canada) was selected as a coastal city with a considerably cooler and drier climate.

The effects of temperature and humidity are modeled from the functions f1(T) and f3(h), present in Equation 2. As a reference, a case with a constant diffusion coefficient in time was used, that is, disregarding the influence of the climatic parameters.

For this analysis, the surface chloride concentration was kept constant over time and the effects of the degree of hydration and the skin effect were not considered in order to facilitate the interpretation of the results regarding the parameters to be studied. Table 4 shows the control variables that make up this study and their respective values. The surface chloride concentration (C_s) and the reference diffusion coefficient ($D_{c,ref}$) were chosen within the ranges found in the literature [10, 12, 26, 28, 29].

Due to the lack of more accurate data, the temperature and relative humidity of the concrete pores were considered in equilibrium with the atmosphere. As reported by Andrade *et al*. [30], the temperature inside the concrete is very similar to the outside temperature. The climatic data of the cities of Florianópolis (SC, Brazil) and João Pessoa (PB, Brazil) were obtained from the National Institute of Meteorology (INMET[2]) for the period 1961 to 1990. The data about the City of Vancouver, (BC, Canada) were provided by the Department of Environment and Climate Change Canada (ECCC[3]) from 1981 to 2010. The values used as input data in the *software* are shown in Table 5.

ii. Solar radiation

This study was carried out for the cities of João Pessoa (PB) and Florianópolis (SC) with the same parameters of the previous item, adding those referring to solar radiation.

The solar radiation is considered in the function f1(T) (Equation 3) from an increase in the external temperature (Equation 30). Monthly average global solar radiation data on a horizontal surface for each month of the year were obtained from the Solarimetric Atlas of Brazil [15]. The other parameters were selected to represent a structure located in the urban area. Table 6 presents the input data in the program for the modeling of solar radiation for João Pessoa and Florianópolis.

3.1.1 Results and discussion

i. Temperature and humidity

Figure 6 shows the variation of the chloride concentration for the

Table 5
Parametric analysis: annual climatic parameters

Climatic parameters		Florianópolis (SC)	João Pessoa (PB)	Vancouver (BC)
Temperature	Maximum (°C)	24.6	27.2	18
	Minimum (°C)	16.5	24.2	3.6
	Day of maximum annual	45	45	210
Relative humidity	Maximum (%)	84	87	81.2
	Minimum (%)	80	73	61.4
	Day of maximum annual	195	195	15

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[2] http://www.inmet.gov.br/portal/index.php?r=clima/normaisclimatologicas

[3] http://climate.weather.gc.ca/climate_normals/results_1981_2010_e.html?stnID=889&autofwd=1

Table 6
Parametric analysis: parameters of solar radiation - João Pessoa (PB) and Florianópolis (SC)

JAN		**FEB**		**MAR**		**APR**	
João Pessoa	Florianópolis	João Pessoa	Florianópolis	João Pessoa	Florianópolis	João Pessoa	Florianópolis
22	18	20	16	20	14	18	12
MAY		**JUN**		**JUL**		**AUG**	
João Pessoa	Florianópolis	João Pessoa	Florianópolis	João Pessoa	Florianópolis	João Pessoa	Florianópolis
16	10	14	8	14	8	18	10
SEPT		**OCT**		**NOV**		**DEC**	
João Pessoa	Florianópolis	João Pessoa	Florianópolis	João Pessoa	Florianópolis	João Pessoa	Florianópolis
20	12	22	16	20	18	20	18

Parameters for calculating increase in temperature		
City	João Pessoa	Florianópolis
Latitude	27.5°	7.0°
Surface slope	90°	90°
Surface azimuth	30°	30°
Reflection coefficient of surroundings	0.5	0.5
Absorption factor	60%	60%
heat transfer coefficient	25 Kcal/m²h °C	25 Kcal/m²h °C

case of constant diffusion coefficient and for the cities of Florianópolis, João Pessoa and Vancouver. Table 7 shows chloride concentration values for the ages of 5, 10, 20 and 50 years for the studied cases.

It can be observed that the rate of increase in the concentration of chlorides varies throughout the year seasonally, presenting reduction in the inclination of the curve in cooler and dry periods.

For all ages, the case at which the diffusion coefficient was kept constant showed higher concentrations. Florianópolis shows, in relation to the case of constant coefficient, reductions of 53.90%, 36.70%, 22.60% and 14.00% for the ages of 5, 10, 20 and 50 years, respectively. On the other hand, João Pessoa shows reductions of 35.81%, 22.41%, 12.96% and 7.93% for these ages. In relation to the same case, Vancouver, due to its low values of f1(T) and f3(h), is the one that shows the greatest reductions, namely 100%, 100%, 97.94% and 86.78%. In relation to the city of João Pessoa, which resulted in the highest concentrations between the three cities, Vancouver has a concentration reduction of 85.64% for the age of 50 years. Figure 7 shows the isoconcentration maps generated by the software for the cases analyzed.

ii. Solar radiation

In this analysis, the parameters of temperature and humidity of the cities of Florianópolis and João Pessoa were considered, with the increase in the temperature generated by the solar radiation in these cities (Equation 30). Figure 8 shows the chloride concentration variation for the cities of Florianópolis and João Pessoa, demonstrating the effect of considering the influence of solar radiation.

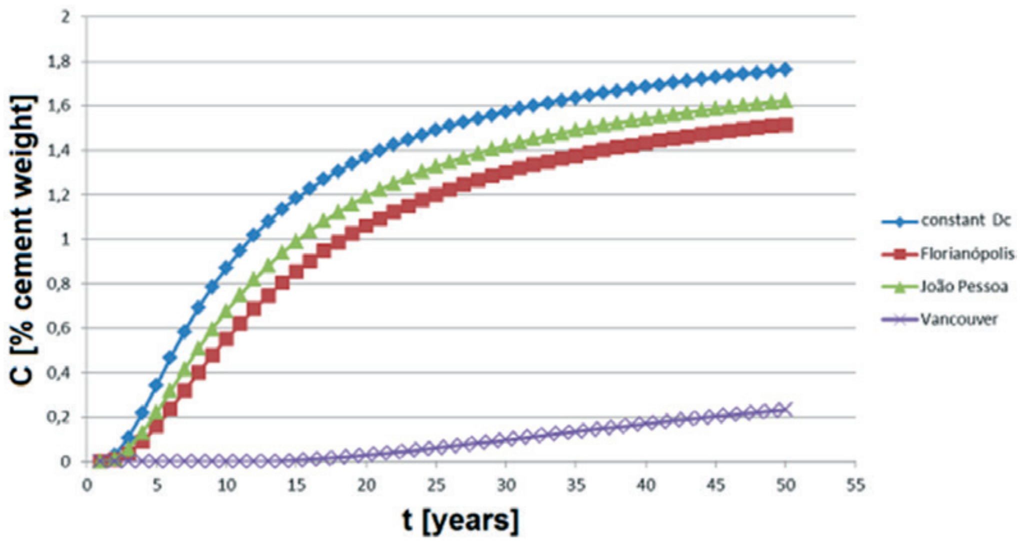

Figure 6
Chloride concentration variation – climatic parameters

Table 7
Chloride concentration values for 5, 10, 20 and 50 years – climatic parameters

Case	Chloride concentration [% of cement weight]			
	5 years	10 years	20 years	50 years
Constant Dc	0.3432	0.8725	1.3710	1.7635
Florianópolis	0.1582	0.5523	1.0612	1.5166
João Pessoa	0.2203	0.6770	1.1933	1.6237
Vancouver	0.0000	0.0000	0.0283	0.2332

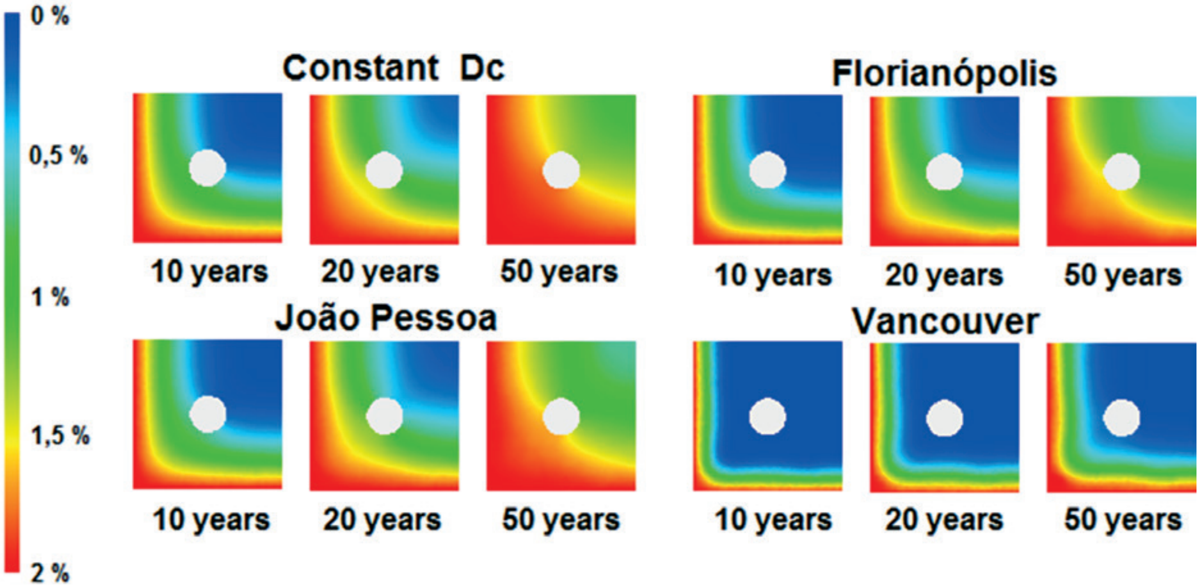

Figure 7
Isoconcentration maps – climatic parameters

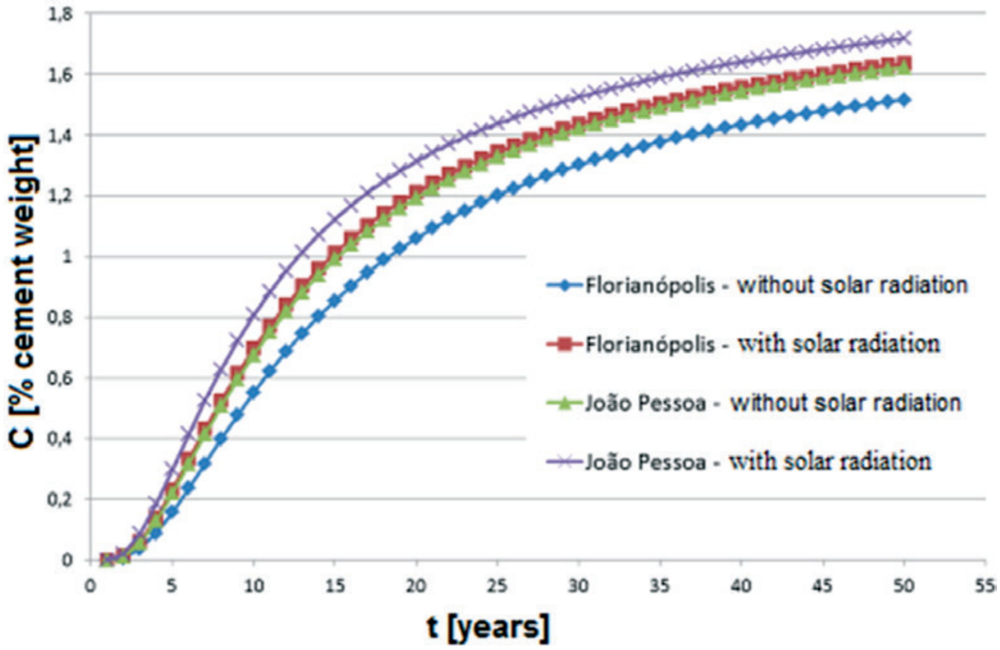

Figure 8
Chloride concentration variation – solar radiation

Table 8
Chloride concentration values for 5, 10, 20 and 50 years – solar radiation

Case	Chloride concentration [% of cement weight]			
	5 years	10 years	20 years	50 years
Florianópolis – without solar radiation	0.1582	0.5523	1.0612	1.5166
Florianópolis – with solar radiation	0.2326	0.6979	1.2124	1.6365
João Pessoa – without solar radiation	0.2203	0.6770	1.1933	1.6237
João Pessoa – with solar radiation	0.2999	0.8079	1.3144	1.7179

Table 8 shows chloride concentration values for the ages of 5, 10, 20 and 50 years for the studied cases.

Through the presented results, it is observed the capacity of the solar radiation to increase the diffusivity of the concrete. With this consideration, the city of Florianópolis presented concentrations of 47.03%, 26.36%, 14.25% and 7.91% higher for the ages of 5, 10, 20 and 50 years, respectively. Accordingly, for the city of João Pessoa, concentrations were 36.13%, 19.34%, 10.15% and 5.8% higher for the same ages.

3.2 *Influence of exposure time on chloride penetration*

With increased exposure time, there is a continuous increase in the degree of hydration, which reduces the permeability of the concrete, also reduces its diffusivity, a value depending on the type of cement and admixtures used.

For this analysis, only the degree of hydration was considered as an intervening factor in the diffusion coefficient, that is, the effects of temperature, relative humidity and solar radiation were not considered so as to facilitate the interpretation of the results regarding the parameters it aims to study. The surface chlorides concentration (Cs) used was 2% in relation to the cement mix, kept constant over time. The values used for the ageing factor (m), which controls the evolution of cement hydration, were 0.264 (ordinary Portland cement - OPC), 0.621 (cement with ground granulated blast furnace slag - GGBS) and 0.699 (fly ash cement - FA).

3.2.1 Results and discussion

The variation of the function f2(t) (Equation 7) over two years for the cases studied is shown in Figure 9. Figure 10 shows the variation of the chloride concentration for the cases of: constant diffusion coefficient, OPC (m = 0.264), GGBS (m = 0.621), and FA concrete (m = 0.699). Table 9 shows chloride concentration values for the ages of 5, 10, 20 and 50 years.

The results show a great influence of the type of cement, the admixtures used and the degree of hydration in the diffusivity of the concrete. Consideration of the degree of hydration led to a reduction in chloride concentration after 50 years of exposure of 73.50% for OPC and 100% for cement with GGBS and FA. It is verified that the effect of the hydration occurs mainly in the early ages, affecting decisively the diffusion of chlorides (Figure 9).

When considering the value of 0.4% as the threshold concentration for the depassivation of the reinforcement, a common value in the technical field, it is estimated that the reinforcement would be depassivated in a little more than 5 years when the effect of the hydration degree is disregarded. In the case of OPC, the

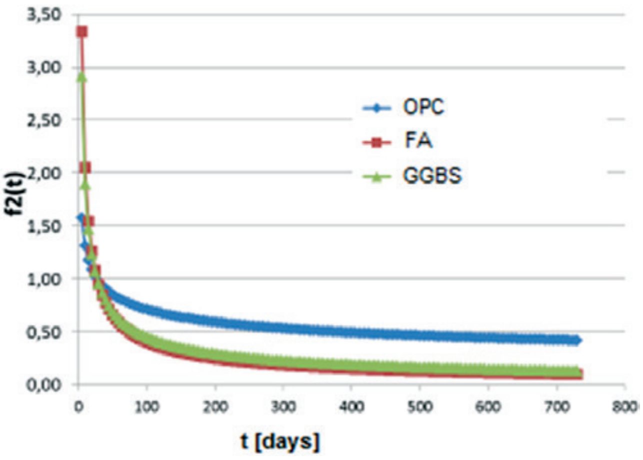

Figure 9
Multiplicative function variation f2 (t) throughout two years

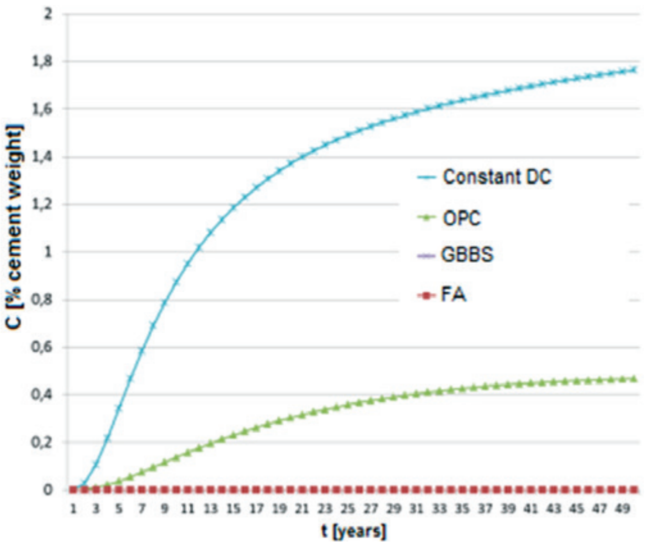

Figure 10
Chloride concentration variation – exposure time

Table 9
Chloride concentration values for 5, 10, 20 and 50 years – exposure time

Case	Chloride concentration [% of cement weight]			
	5 years	10 years	20 years	50 years
Constant Dc	0.3432	0.8725	1.3710	1.7635
Ordinary Portland cement; m=0.264	0,0370	0,1367	0,3033	0,4674
Ground Granulated Blast-furnace slag; m=0.621	0	0	0	0
Fly Ash; m=0.699	0	0	0	0

Table 10
Parametric analysis: control variables

Control variables		Value
Boundary conditions	Initial concentration (C0)	0 %
Diffusion coefficient	Reference diffusion coefficient ($D_{c,ref}$)	1x10-12 m²/s

depassivation would occur at 30 years. Considering the use of GGBS and FA, depassivation would occur at ages greater than 50 years.

3.3 Influence of different surface concentration models on chloride penetration

For this analysis, the chloride diffusion coefficient was kept constant over time, that is, the effects of temperature, relative humidity, degree of hydration and solar radiation on the diffusion coefficient were not considered so as to facilitate the interpretation of the results regarding the parameters to be studied. Table 10 shows the control variables that make up this study and their respective values.
This study used the surface concentration data presented by Bentz *et al*. (1996) *apud* Song [29], employed by Song [29] in proposing his model. From the parameters presented by the author, non-linear regression was performed to adjust the curves of the other models. For the concentration values of chloride in % of concrete weight, for obtaining concentration in relation to % of cement weight, a specific weight of 2300 kg/m³ and cement content in the concrete of 350 Kg/m³ was considered. The parameters found for each model are presented in Table 11. Figure 11 shows the curves obtained with these parameters. The values obtained are equivalent, according to the technical literature, to a zone of tidal variation [31].

3.3.1 Results and discussion

Figure 12 shows the chloride concentration variation for the five surface concentration approaches used in this study. Table 12 shows chloride concentration values for the ages of 5, 10, 20 and 50 years for the studied cases.
The constant surface concentration approach produced the highest chloride concentration values for the first 30 years. This is because, according to Figure 11, the surface concentration was the highest in the early ages. For higher ages, this approach tends to present lower values than the other models. The model of Uji *et al*. [26], presented the lowest concentrations of chlorides during almost the entire estimated time. However, at ages close to

Table 11
Parameters of surface concentration obtained through non-linear regression

Model	Equation	Parameters
-	$C_S = cte$	Cs = 5.1541
Uji *et al.* (1990)	$C_S = S\sqrt{t}$	S = 2.51e-05
Collins and Grace (1997)	$C_S = C_{s,ult} \cdot \frac{t}{t + T_{CS}}$	Cs,ult = 0.8651 ; Tcs = 533.5267
Ann *et al.* (2009)	$C_S = C_0 + k\sqrt{t}$	C0 = 3.3593 ; k = 0.3488
Song *et al.* (2008)	$C_S = C_0 + \alpha \ln t$	C0 = 3.0431; α = 0.6856

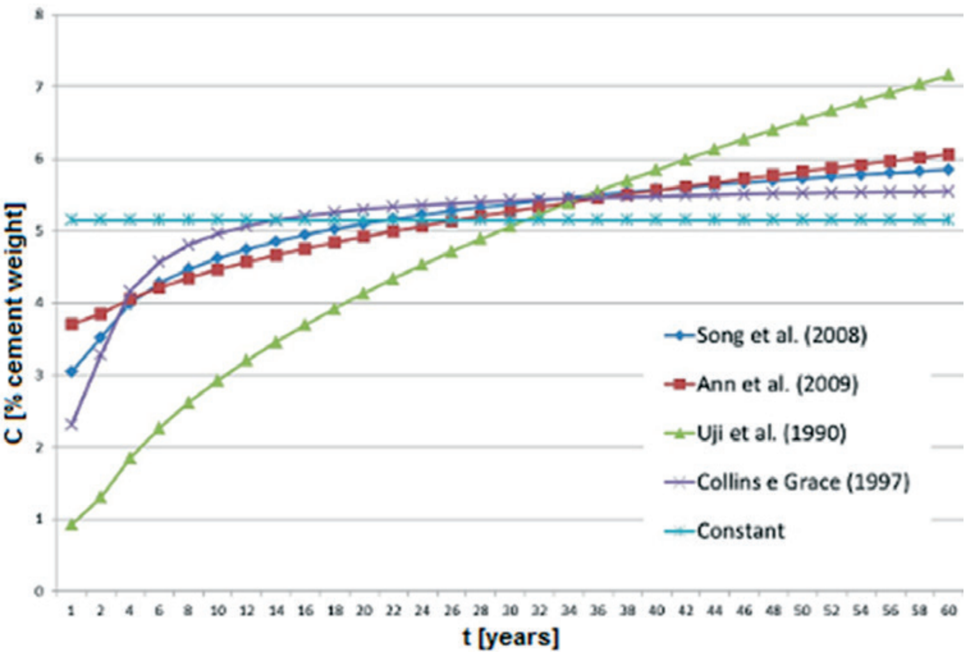

Figure 11
Surface concentration variation curves used in parametric analysis

50 years, it already showed higher concentrations, with a tendency to increase distancing at future ages.

The other models [27-29] resulted in values of chloride concentration very close throughout the study period. However, the curve referring to the Ann *et al*. [28] tends to distance itself from the other two because the surface concentration of this model tends to grow indefinitely with time. On the other hand, the models of Collins and Grace [27] and Song *et al*. [29] tend to continue to present close values, since their surface concentration curves have some aspects in common, starting at intermediate values and approaching a constant value in recent years.

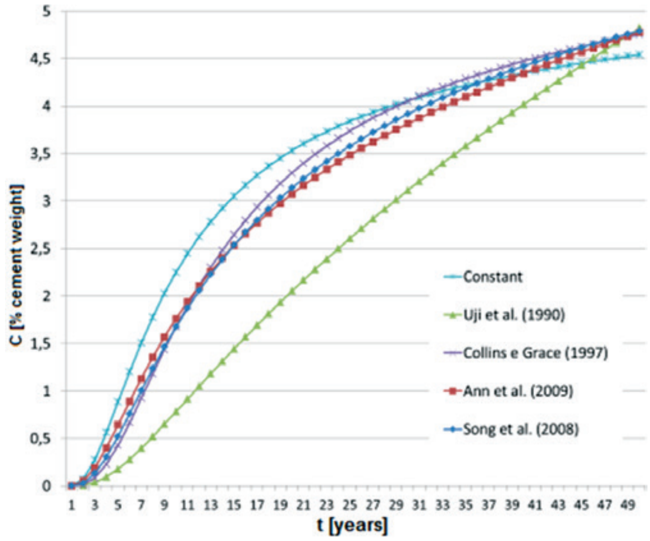

Figure 12
Chloride concentration variation – surface concentration

4. Analysis of different cover thicknesses for the cities of Vitória (ES) and Florianópolis (SC)

The thickness and quality of concrete cover are two of the main factors that determine the durability of the structures. Thus, NBR 6118 [7] establishes the quality of the concrete and the minimum thickness that must be met for each class of environmental aggressiveness. In order to ensure minimum coverage (c_{min}), the standard prescribes that the design and execution should consider the nominal cover (c_{nom}), which is the minimum cover plus the ex-

Table 12
Chloride concentration values for 5, 10, 20 and 50 years – surface concentration

Approach	Chloride concentration [% of cement weight]			
	5 years	10 years	20 years	50 years
Constant Cs	0,8845	2,2484	3,5331	4,5446
Uji *et al.* (1990)	0,1761	0,7829	2,0521	4,8225
Collins and Grace (1997)	0,4270	1,6747	3,2969	4,7543
Ann *et al.* (2009)	0,6431	1,7610	3,0757	4,7780
Song *et al.* (2008)	0,5220	1,6745	3,1381	4,7933

ecution tolerance (Δc = 10 mm, in current works). According to the standard, beams and columns in reinforced concrete, located in areas of marine aggression class, should have a nominal cover of 40 mm, that is, a minimum cover of 30 mm ($c_{mín} = c_{nom} - \Delta c = 30$ mm). Thus, 20 mm, 30 mm and 40 mm cover thicknesses are analyzed for the cities of Vitória (ES) and Florianópolis (SC), demonstrating the effects on the service life. For this, a 20 cm wide and 40 cm high facade beam in naked concrete located in a marine atmosphere zone is considered.

Due to the lack of more precise data, specific to each region, we employed the surface concentration model by the Uji *et al.* [26], with parameter "S" equal to 5.57 x e-6 1 / √s, indicated by the author as typical of marine atmosphere zone. Only one of the faces of the beam was considered exposed (Figure 13). The evolution of the surface concentration used for the two cities is shown in Figure 14.

Due to the lack of real data, the reference diffusion coefficient was adopted as $1x10^{-12}$ m² / s, measured at 120 days at 23° C, a value consistent with those found in the literature. Climatic data from the city of Vitória (ES) and Florianópolis (SC) were obtained from the National Institute of Meteorology (INMET). Due to the lack of more accurate data, the temperature and relative humidity of the concrete pores were considered in equilibrium with the atmosphere. As reported by Andrade *et al.* [30], the temperature inside the concrete is very similar to the external temperature. The activation energy was adopted as 44.6 kJ/K.mol, referring to a concrete with water/cement ratio of 0.5.

In order to consider the degree of hydration, the type of cement used should be determined. The most used cement in Vitória is the CP – III. On the other hand, in Florianópolis, the CP - II and the CP - IV are predominant. However, due to the great sensitivity of the diffusion coefficient in relation to the ageing factor (m), the great variability of this parameter and the lack of accurate data for each type of cement, a less favorable situation was considered, with a Concrete of CP-I cement, of factor "m" equal to 0.264.

The monthly average global solar radiation data received by a horizontal surface for each month of the year in the cities of Vitória and Florianópolis were obtained from the Solarimetric Atlas of Brazil [15]. The other parameters for calculating the temperature increase due to solar radiation were chosen to represent a structure in the urban area. The parameters used as input data in the software program are shown in Tables 6, 13 and 14.

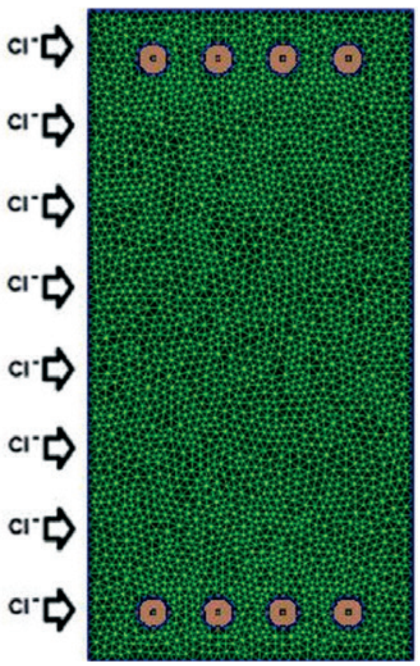

Figure 13
Geometry and exposed surface

4.1 Results and discussion

Figure 15 and Figure 16 show the variation of chloride concentration for the concrete covers studied for the cities of Vitória and Florianópolis, respectively. Table 15 shows chloride concentration values for the ages of 5, 10, 20 and 50 years for the study cases. Figure 17 shows the isoconcentration maps generated by the software for the cases analyzed.

It can be seen that the concentrations reached in the two cities

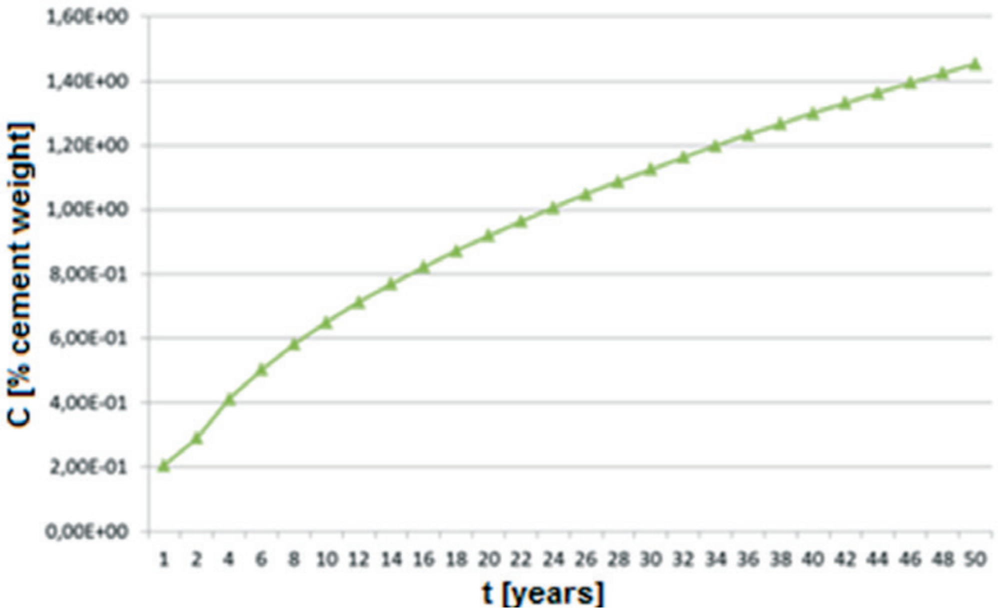

Figure 14
Surface concentration adopted (marine atmosphere zone)

Table 13
Application of the model: input parameters

<table>
<tr><th colspan="2">Parameters</th><th colspan="6">Value</th></tr>
<tr><td rowspan="2">Geometry</td><td>Dimensions</td><td colspan="6">20 cm x 40 cm</td></tr>
<tr><td>Concrete cover</td><td colspan="2">20 mm</td><td colspan="2">30 mm</td><td colspan="2">40 mm</td></tr>
<tr><td rowspan="4">Mesh</td><td>Type of elements</td><td colspan="6">Linear triangular</td></tr>
<tr><td>Size of elements</td><td colspan="6">0.006</td></tr>
<tr><td>Number of nodes</td><td colspan="2">3256</td><td colspan="2">3253</td><td colspan="2">3234</td></tr>
<tr><td>Number of elements</td><td colspan="2">6211</td><td colspan="2">6205</td><td colspan="2">6167</td></tr>
<tr><td rowspan="2">Time parameters</td><td>Final time (T)</td><td colspan="6">50 years</td></tr>
<tr><td>Time step (Δ_t)</td><td colspan="6">5 days</td></tr>
<tr><td rowspan="3">Boundary conditions</td><td>Initial concentration (C_0)</td><td colspan="6">0 %</td></tr>
<tr><td>Chloride surface concentration (C_s)</td><td colspan="6">Uji *et al.* (1990)
$S = 5.57\text{e-}6\ 1/\sqrt{s}$</td></tr>
<tr><td>Cement content</td><td colspan="6">350 kg/m^3</td></tr>
<tr><td rowspan="6">Diffusion coefficient</td><td>Reference Diffusion Coefficient (Dc,ref)</td><td colspan="6">1x10-12 m^2/s</td></tr>
<tr><td>Reference Temperature (Tref)</td><td colspan="6">23 °C</td></tr>
<tr><td>Reference age (tref)</td><td colspan="6">120 days</td></tr>
<tr><td>Activation Energy (U)</td><td colspan="6">41.8 kJ/mol</td></tr>
<tr><td>ageing factor (m)</td><td colspan="6">0,264</td></tr>
<tr><td>Humidity parameter hc</td><td colspan="6">0,75</td></tr>
<tr><td rowspan="4">Diffusion coefficient</td><td>City:</td><td colspan="3">Vitória</td><td colspan="3">Florianópolis</td></tr>
<tr><td>Maximum (°C)</td><td colspan="3">26,9</td><td colspan="3">24,6</td></tr>
<tr><td>Minimum (°C)</td><td colspan="3">21,7</td><td colspan="3">16,5</td></tr>
<tr><td>Day of maximum annual</td><td colspan="3">45</td><td colspan="3">45</td></tr>
<tr><td rowspan="3">Relative humidity</td><td>Maximum (%)</td><td colspan="3">80</td><td colspan="3">84</td></tr>
<tr><td>Minimum (%)</td><td colspan="3">77</td><td colspan="3">80</td></tr>
<tr><td>Day of maximum annual</td><td colspan="3">285</td><td colspan="3">195</td></tr>
</table>

Table 14
Application of the model: solar radiation parameters – Vitória (ES)

<table>
<tr><th colspan="4">Daily global solar radiation on a monthly average received by a horizontal surface for each month of the year [MJ/m².day]</th></tr>
<tr><td>**JAN**</td><td>**FEB**</td><td>**MAR**</td><td>**APR**</td></tr>
<tr><td>18</td><td>18</td><td>18</td><td>14</td></tr>
<tr><td>**MAY**</td><td>**JUN**</td><td>**JUL**</td><td>**AUG**</td></tr>
<tr><td>14</td><td>12</td><td>12</td><td>14</td></tr>
<tr><td>**SEPT**</td><td>**OCT**</td><td>**NOV**</td><td>**DEC**</td></tr>
<tr><td>14</td><td>16</td><td>16</td><td>16</td></tr>
</table>

<table>
<tr><th colspan="2">Parameters for calculating increase in temperature</th></tr>
<tr><td>Latitude</td><td>20,3 °</td></tr>
<tr><td>Surface slope</td><td>90 °</td></tr>
<tr><td>Surface azimuth</td><td>30 °</td></tr>
<tr><td>Reflection coefficient of surroundings</td><td>0,5</td></tr>
<tr><td>Absorption factor</td><td>60 %</td></tr>
<tr><td>heat transfer coefficient</td><td>25 Kcal/m²h°C</td></tr>
</table>

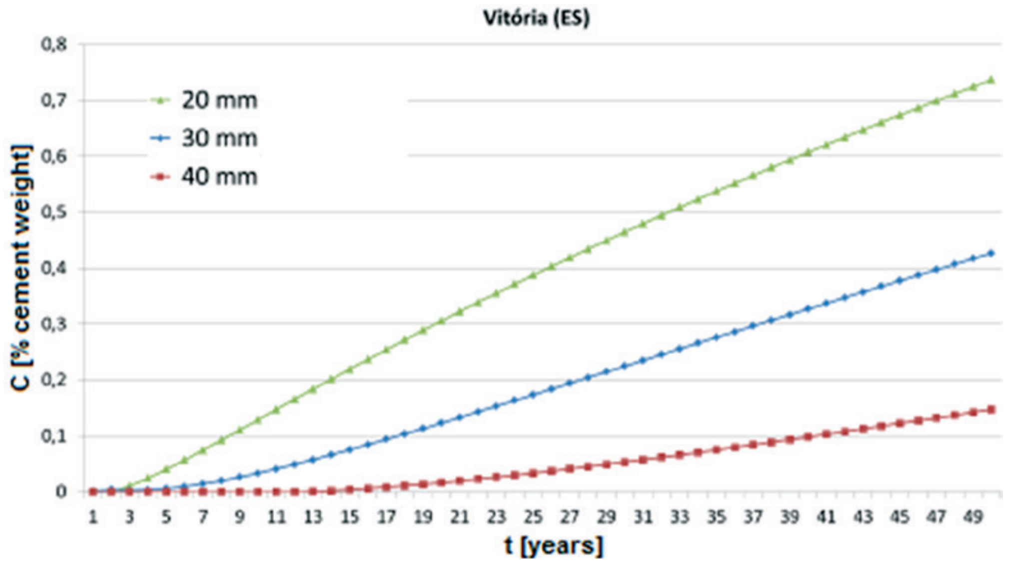

Figure 15
Chloride concentration variation in Vitória, ES

were not very distinct, and after 50 years, Vitória presented values 1.11%, 1.99% and 6.51% higher compared to Florianópolis, for thicknesses of cover of 20 mm, 30 mm and 40 mm, respectively. It is important to point out that, because it is a hypothetical case and because of the lack of data, in this study the same surface concentration was adopted in the two cities, characterizing a zone of marine atmosphere. However, this value tends to change with the location and distance of the sea, influencing the chloride concentration.

The results also demonstrate the great importance of the cover thickness. For the city of Vitória, the case with 30 mm cover has concentrations 85.06%, 74.01%, 59.71% and 42.08% lower than the case with 20 mm thickness for the ages of 5, 10, 20 and 50 years, respectively. The 40 mm cover beam obtained values of concentration 100%, 100%, 94.54% and 80.01% lower for the same ages when compared to the same case. Similar results are obtained for Florianópolis.

Considering the value of 0.4% as the concentration threshold for the depassivation of the reinforcement, a common value in the technical field, the service life obtained for the beam with 20 mm of cover is around 26 years for both cities. For the thickness of 30 mm, the depassivation occurs at 48 years, also in both cities. That is, the increase of 10 mm in cover thickness led to an increase of 84.62% in the service life of the part. The 40 mm cover, which provides the longest service life among the three, presents, after 50 years, a concentration of 0.1444% for the city of Vitoria and 0.1384% for Florianópolis, with a high residual service life.

5. Conclusions

Although the corrosion of reinforcements by chloride attack has been a very much studied topic since the 70's, there are many gaps in the knowledge of its processes. A considerable number of service life models have already been developed; however, there is still no widely accepted approach that has managed to effectively reach the market.

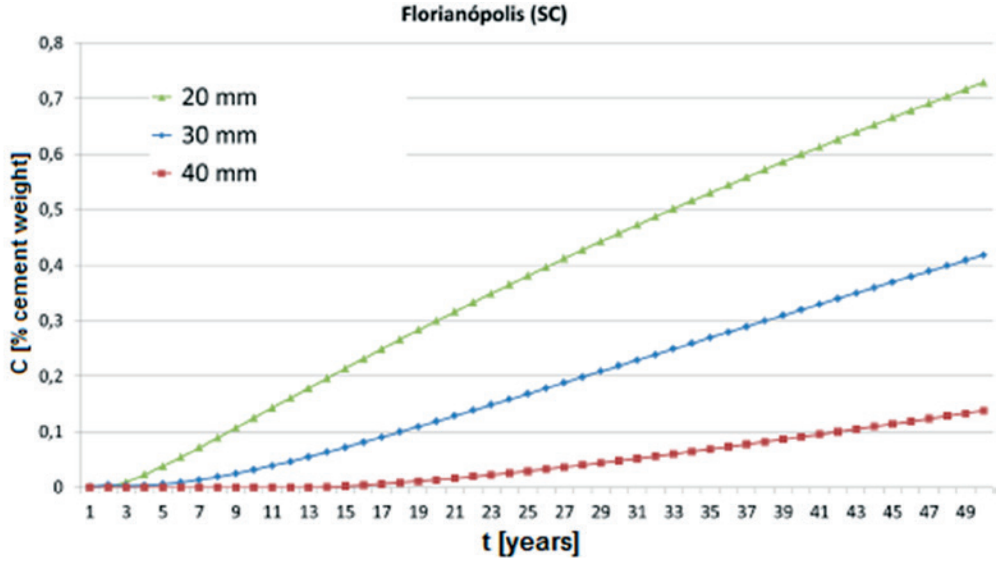

Figure 16
Chloride concentration variation in Florianópolis – SC

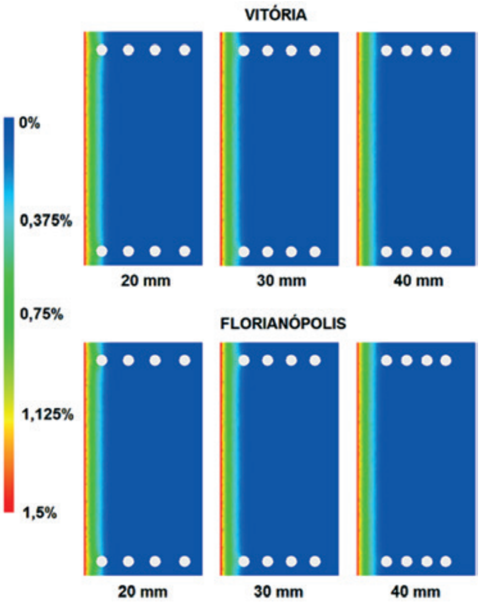

Figure 17
Isoconcentration maps – concrete covers of 20 mm, 30 mm and 40 mm

This study presents a model of penetration of chlorides by diffusion in structures of reinforced concrete. This model foresees the evolution of the chloride concentration over time, as well as the time required, in a given situation, so that the chloride limit for the depassivation of the reinforcement is reached. The software developed has a user-friendly interface (Figure 2) and data entry windows that allow the manipulation of all parameters considered, which facilitates analyses of the influence of each variable.

5.1 Parametric analyses

In order to help understand the physical models that involve the various factors in chloride penetration, a parametric analysis was carried out, considering the influence of climatic parameters (temperature, humidity and solar radiation), the influence of the time of exposure (degree of hydration) and the influence of different approaches of surface concentration of chlorides. From these analyzes, we conclude:

- The lower the temperature and humidity, the lower the penetration of chlorides. Thus, the increase in the concentration of chlorides at a given point varies throughout the year, according to the climatic parameters.
- Cities with different climates presented very different values of diffusion coefficient and concentration of chlorides, which suggests completely distinct times of repair. The greatest tendency for chloride penetration will occur in humid summers and the lowest in dry winters. Also, for temperatures close to zero this phenomenon is greatly reduced and, for humidities below 50%, it is practically non-existent.
- Solar radiation has the capacity to increase the diffusivity of the concrete in a significant way, even for cities where the radiation is not so intense. Thus, non-consideration of solar radiation can lead to overestimated service life values.
- We can see a great influence of the type of cement used and the degree of hydration in the diffusivity of the concrete. This consideration led to a remarkable reduction of chloride concentration in the analyzed cases, increasing the initiation period from 5 years to 30 years in the case of OPC and well above 50 years for the cases of GGBS and FA, where, even after 50 years, the chloride front had not yet reached the reinforcement.
- There is great sensitivity of the diffusion coefficient and chloride concentration in relation to the ageing factor (m). However, there is no significant variety of studies addressing this factor for several types and levels of admixtures, an important condition to increase the reliability of service life prediction.
- Consideration of a constant surface concentration produces higher chloride concentration values at lower ages, eventually being exceeded by other models. For higher ages, the curves referring to the approaches by Uji *et al*. [26] and Ann *et al*. [28] tend to present higher values. The models by Collins and Grace [27] and Song *et al*. [29], tend to present intermediate values, approaching a constant value.
- It is important to note that one of the factors that make it difficult to use models such as the one presented here is the lack of available data on the concentration of chlorides in the literature, for example, to define the surface concentration of chlorides in certain areas or zones of aggressiveness.
- Considering or not considering each factor involved in the

Table 15
Chloride concentration values for 5, 10, 20 and 50 years

Approach	Chloride concentration [% of cement weight]			
	5 years	10 years	20 years	50 years
Vitória –20 mm concrete cover	0,0404	0,1291	0,3060	0,7373
Vitória – 30 mm concrete cover	0,0060	0,0336	0,1233	0,4270
Vitória – 40 mm concrete cover	0	0	0,0167	0,1474
Florianópolis – 20 mm concrete cover	0,0384	0,1252	0,3001	0,7292
Florianópolis – 30 mm concrete cover	0,0057	0,0319	0,1191	0,4187
Florianópolis – 40 mm concrete cover	0	0	0,0139	0,1384

phenomenon of diffusion can lead to major changes in the definition of the initiation period, depending on the condition of the structure – location, climatic parameters, surface concentration, type of cement used, skin layer condition, etc. That is, the importance of each parameter is not constant, but will depend on the specific case and the adoption of inappropriate models can lead to large errors in the indication of time for corrosion.

5.2 Analysis of different concrete cover thicknesses for the cities of Vitória (ES) and Florianópolis (SC)

- The use of the microclimates of each city did not generate major changes in the estimated service life, since the surface concentration used was the same.
- The results obtained corroborate the cover thicknesses presented in NBR 6118 [7]. For the cases studied, a 26-year life span was obtained for 20 mm concrete cover and 48 year for 30 mm concrete cover, minimum thickness for beams and columns located in areas of marine aggression class. The nominal cover specified by the standard for this case of 40 mm resulted in low chloride concentration values after 50 years.
- NBR 6118 [7] still adopts as its main tool the definition of minimum concrete cover thickness and minimum qualities of cover concrete. The use of deterministic models allows the quantitative evaluation of the service life for specific real cases, expressed in number of years. It is important to obtain data on surface concentration and diffusion coefficient for use in real constructions.

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