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Durability of concrete structures in marine atmosphere zones – The use of chloride deposition rate on the wet candle as an environmental indicator

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ABSTRACT

Durability of concrete structures under marine environments has been studied for a long time. This work was focused on marine atmosphere zone and studied the deposition of chlorides on wet candle devices and its relation with chlorides accumulated into concrete. Concrete specimens with three different mixtures were exposed at places located at four different distances from the sea. Periodically, chloride profiles were obtained and analysed taking into account environmental data. Results of numerical extrapolations show that chloride deposition rate on the wet candle can be used as an environmental indicator, helping to preview the expectancy of service life of concrete structures or suggesting minimum concrete cover thicknesses for a required service life. Regarding the studied region, service life decreases between 30% and 60% were observed when changing chloride deposition from 120 mg/m^2 day to 500 mg/m^2 day, which shows that chloride deposition plays an important role as an environmental indicator on service-life analysis of concrete structures in marine atmosphere zone.

1. Introduction

Durability of concrete structures under marine environment has been studied for a long time. In the last years, studies under natural exposure have been more common. However, most of them focus underwater structures, structures in tidal zone or in environments closer to the sea [1–4]. Researches that consider concrete structures behaviour only in marine atmosphere zone are scarce and only a few of them take into account the differences on concrete interaction with environment when concrete structures are placed at different distances from the sea and, thus, are subjected to different levels of chloride aggressiveness [5–8].

Chloride aggressiveness in marine atmosphere zone has its origin in aerosol production, which can take place either in the surf zone and or in the open sea [9,10]. This mechanism, which is strongly influenced by wind characteristics [11], is more effective in seashore due to the breaking waves movement, which contributes to produce more and larger drops [11]. After being produced, marine aerosol is transported inland by wind. During this transport, particles that compose marine aerosol settle after having covered a certain distance from the sea, which depends on their weight, wind characteristics and obstacles present in aerosol trajectory [11–14]. As a consequence, a strong decrease tendency of salt concentrations in atmosphere takes place in the first meters away from the sea [6–8,14]. This way, concrete structures placed at different sites in marine atmosphere zone are subjected to different levels of chloride concentration in atmosphere and thus may present different durability performances [6,8].

Some studies carried out in marine atmosphere zone present relationships between salt presence in atmosphere and metallic corrosion rate [14]. Other studies, which are focused on atmospheric parameters, show the salinity decay of marine aerosol when being transported inland [7,9,15]. On the other hand, studies that show the relationship between chloride presence in atmosphere and concrete durability are still scarce. Some efforts done in this way show that, as in aerosol salinity, there is a similar decrease tendency for the total amount of chlorides that penetrate into concrete structures built in marine atmosphere zone [5,6,8,16]. These studies, which were carried out under natural exposures, observed decreases up to 70% in chloride penetration into concrete in the first hundred meters from the sea and one of the previous papers published by the authors presented relationships between chlorides form marine aerosol and those that penetrate into concrete [16]. However, long-term data and service life analyses are still needed to improve this kind of analysis.

Considering the measurement of salt presence in atmosphere, cascade collectors [17], pumping systems [18] or simplified capturing systems based on deposition measurements [19,20] are commonly employed in marine atmosphere zone with this objective.

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Fig. 1. Wet candle device.

Among them, the wet candle device (Fig. 1) is usually used for this purpose, as part of standardized procedures to measure the amount of chloride salts which is captured from the atmosphere on a prescribed exposed area of the apparatus [21].

Taking into account the lack of studies connecting environmental characteristics with durability performance of concrete structures, the aim of this paper is to analyse the use of chloride deposition rate on the wet candle device as an environmental indicator to preview tendencies of chloride accumulation into concrete and suggest different durability requirements for concrete structures exposed in marine atmosphere zone, considering different characteristics of the material and environment. Curves representing the relationship of this environmental indicator with chloride accumulation into concrete in marine atmosphere zone are presented. Previous author's papers contributed to analyse marine aerosol behaviour [7] and its interaction with concrete structures [6,16]. However, it is in the current paper that long-term data and service-life analysis could be incorporated.

2. Chloride penetration into concrete and its modelling

Chlorides from marine aerosol deposit on concrete surface and from that penetrate into bulk concrete. After a certain time, they reach the reinforcement and when a certain critical content of chlorides is reached the corrosion process is started, depending on the other requirements to enable the formation of the corrosion cell [5]. This chloride threshold has been widely accepted as 0.4% of cement mass, although it is known that it can vary in a significant range depending on environment and material characteristics [22].

In marine atmosphere zone, concrete structures are subjected to wetting and drying cycles on their surface layers [23]. Thus, the chlorides are absorbed by capillary sorption in partially saturated concrete (convection zone) and remain inside during dry periods. This leads to a fluctuation of chloride concentration in this external region and reach a maximum chloride concentration in the end of the convection zone [24,25]. This behaviour, which is also influenced by carbonation of concrete and differences on concrete porosity between surface and bulk concrete, represents the "skin effect" [26], which contributes to different transport characteristics between the "skin" and bulk concrete.

Modelling of chloride penetration into concrete has been traditionally done by the use of Fick's second law, assuming as constants the surface chloride concentration and the diffusion coefficient [27]. Advances have been obtained on this modelling considering the effect of variables like time [28,29], temperature [30,31], water saturation degree of concrete [32], etc., on chloride transport. Taking into account the multiple influence of variables on chloride transport into concrete, numeric models have been proposed to represent these phenomena. This way, finite difference method has been used in some approaches [32–34] and finite element method has been used in more sophisticated models [24,30,35]. This work used the finite difference method and incorporated some simplifications described in Section 5.2.

3. Experimental work

Experimental work was divided in two parts. The first one was dedicated to environmental characterization and the second focused on the study of chloride concentrations in concrete. The whole study was carried out in the northeast of Brazil (Fig. 2).

3.1. Environmental characterization

The environmental characterization was done by climatic and sea-salt data. Climatic data were collected by a Brazilian Government weather station located in the region where the research took place and it was done on temperature, relative humidity, and wind speed and wind direction. The UTC (coordinated universal time) references were followed on these measurements.

Sea-salt aerosol was studied by measuring airborne chloride deposition on the wet candle device (Fig. 1), according to the specifications established in the ASTM standard G140 [21]. These devices were placed at the height of 1.5 m from the ground and, simultaneously, located at 10, 100, 200, 500 and 1100 m from the sea, according to the geographical coordinates shown in Fig. 2. The area chosen was as plain as possible, to avoid significant variation in height, and free of obstacles to reduce the effect of ground roughness in the measured data. The seashore in the studied region is characterized by a plain and flat surface covered with sand and with low presence of rocks or corals. Samples from the

Exposure point	Distance from the sea (m)	Latitude	Longitude
1	10	7°1’42.9”	34°49’50.1”
2	100	7°1’42.2”	34°49’52.8”
3	200	7°1’41.0”	34°49’55.8”
4	500	7°1’47.2”	34°50’13.1”
5	1100	7°1’47.2”	34°50’13.1”

Fig. 2. Region where the experimental work took place.

wet candle device were collected monthly and analysed by potentiometric titration throughout the research period.

3.2. Chloride concentration in concrete

Prismatic concrete specimens of 0.15 × 0.15 × 1.40 m were cast using a Brazilian cement CPIIF (Filler-modified Portland), which chemical composition and physical properties are presented in Table 1. Water to cement ratios were set at 0.50, 0.57 and 0.65, representing materials with a large range of porosity characteristics and composing the mixtures C1 – C3 (Table 2). Compressive strength, concrete slump and mercury intrusion porosimetry were also measured to characterize the concretes (Table 2). Although another kind of cement was incorporated in the whole study, it was not presented in this paper due to not taking part in the long-term analyses.

Table 1
Chemical composition and physical properties of cement.

Composition/property	Filler-modified Portland cement
SO_3 (%)	3.21
SiO_2 (%)	18.11
Al_2O_3 (%)	4.31
Fe_2O_3 (%)	2.27
CaO (%)	59.87
MgO (%)	3.61
Na_2O (%)	0.21
K_2O (%)	1.51
Insoluble residue – IR (%)	1.45
Loss on ignition – Li (%)	5.50
C_3A content (%)	6.80
Blaine (cm^2/g)	3650
Specific density (g/cm^3)	3.06

The specimens were cured in a wet chamber for 7 days before being placed at locations 10, 100, 200 and 500 m away from the sea, at the same monitoring stations used for measuring chloride deposition, according to the geographical coordinates in Fig. 2. The monitoring station at 1100 m from the sea was not used to study chloride concentration in concrete. The underground part of the specimens was covered with an impermeable membrane to prevent the possibility of a wicking effect from the ground. In a similar way, the specimen faces not perpendicular to the predominant winds were also waterproofed with a polyurethane coating to simulate the unidirectional transport of chlorides into concrete (Fig. 3).

After 6, 10, 14, 18 and 46 months of exposure, samples were extracted from the specimens to obtain chloride profiles in concrete. The first step in obtaining the samples was to remove (by drilling), from the prismatic specimens, 7.0 cm diameter cores. The direction of coring was parallel to the historically established predominant wind direction. Care was taken to avoid washing effect on specimen surfaces, protecting them with a waterproof tape. The first millimetre of each core was powdered and was used as a surface

Table 2
Concrete mixtures and properties.

Concrete	C1	C2	C3
Cement (kg/m^3)	406	356	320
Sand (kg/m^3)	769	812	840
Aggregate (kg/m^3)	947	947	947
Plasticiser (kg/m^3)	1.22	1.06	–
w/*c* ratio	0.50	0.57	0.65
Slump (mm)	8 ± 1	8 ± 1	8 ± 1
Compressive strength (MPa) – 28 days	31.0	27.0	20.3
Total porosity (mercury intrusion porosimetry – 180 days) – (vol.%)	13.0	13.7	15.7

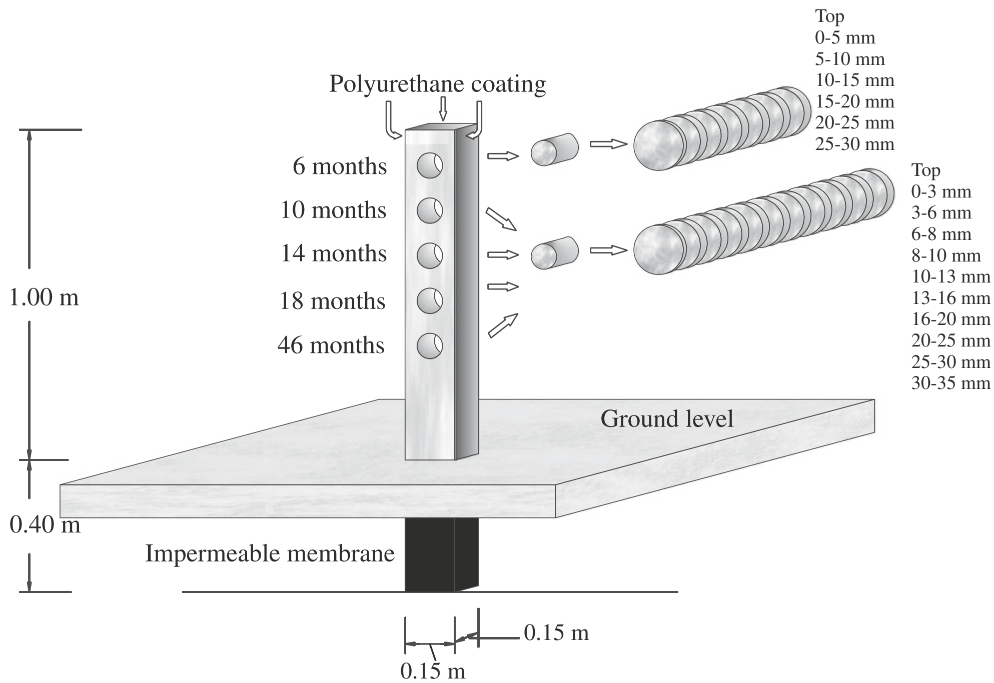

Fig. 3. Schematic design of concrete specimens used in the study and details of cores for samples extraction and chloride content analyses.

sample. Additional samples, also powdered, were taken up to the depth of 30 or 35 mm, according to the distribution presented in Fig. 3. For each sample the total chloride content was determined by potentiometric titration, following the procedures of the International Union of Laboratories and Experts in Construction Materials, Systems and Structures (RILEM) [36].

Furthermore, measurements of the water saturation degree of concrete porous network were also done along the observation period using a methodology based on mass measurements of concrete specimens over time and comparisons with saturated mass of these specimens [37,38]. This methodology is not discussed here, but the behaviour of this variable for the concretes studied in this paper is incorporated to the numeric approach used in Section 5.2. Detailed data of this variable and methodology can be seen in the Ref. [39].

4. Results

4.1. Environmental characterization

The region chosen for the experimental work is representative of a typical tropical climate. The local temperature shows little variation, ranging roughly from 20 °C to 30 °C. The relative humidity stays usually between 60% and 80%, with higher values during longer rain periods. Winds are usually from S–SE–E directions and their speeds are typically low and stay in the range between 1.0 and 4.0 m/s daily average. More detailed data can be assessed in a previous published paper by the authors [40].

The results of chloride deposition on the wet candle device are shown in Fig. 4 as monthly average data. The data show a clear reduction of airborne salinity in the first 200 m, which agrees with previous published data [5,14]. The reduction in chloride deposition rates after the first two hundred meters demonstrate that chloride aggressiveness reduction is stronger in the first land zones. After this distance from the sea, there are also differences on measured data, but they are less accentuated. A deeper discussion about the wet candle results and its influencing variables was done in previous papers [40,41]. Here, only aspects necessary for the aim of this paper are incorporated.

4.2. Chloride profiles in concrete

During the experimental study, dozens of chloride profiles were obtained. The profiles obtained up to 18 months of exposure are fully described in another document [39] and show typical increase tendencies of chloride concentrations with *w*/*c* ratio and with time. The influence of material characteristics, concerning cement composition and concrete porosity, as well as the environmental influence are also discussed in a previous paper [16]. Here, results of a longer exposure time are added. Fig. 5 shows some of the chloride profiles obtained up to 46 months of exposure, which exemplify a long-term behaviour.

Profiles show that there is a clear increase in chloride content over time, as a consequence of a continuous exposure to marine

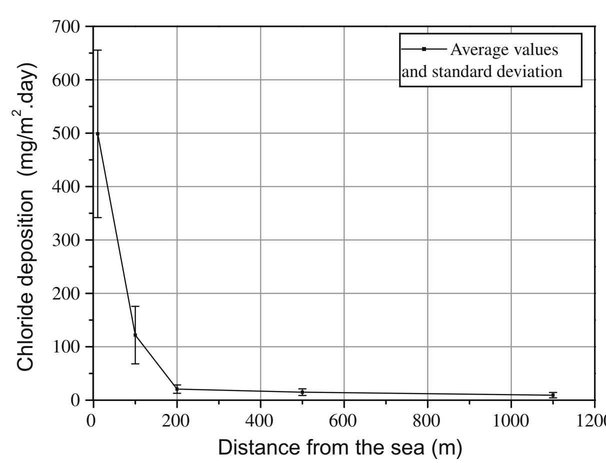

Fig. 4. Chloride deposition on the wet candle device at 10, 100, 200, 500 and 1100 m from the sea.

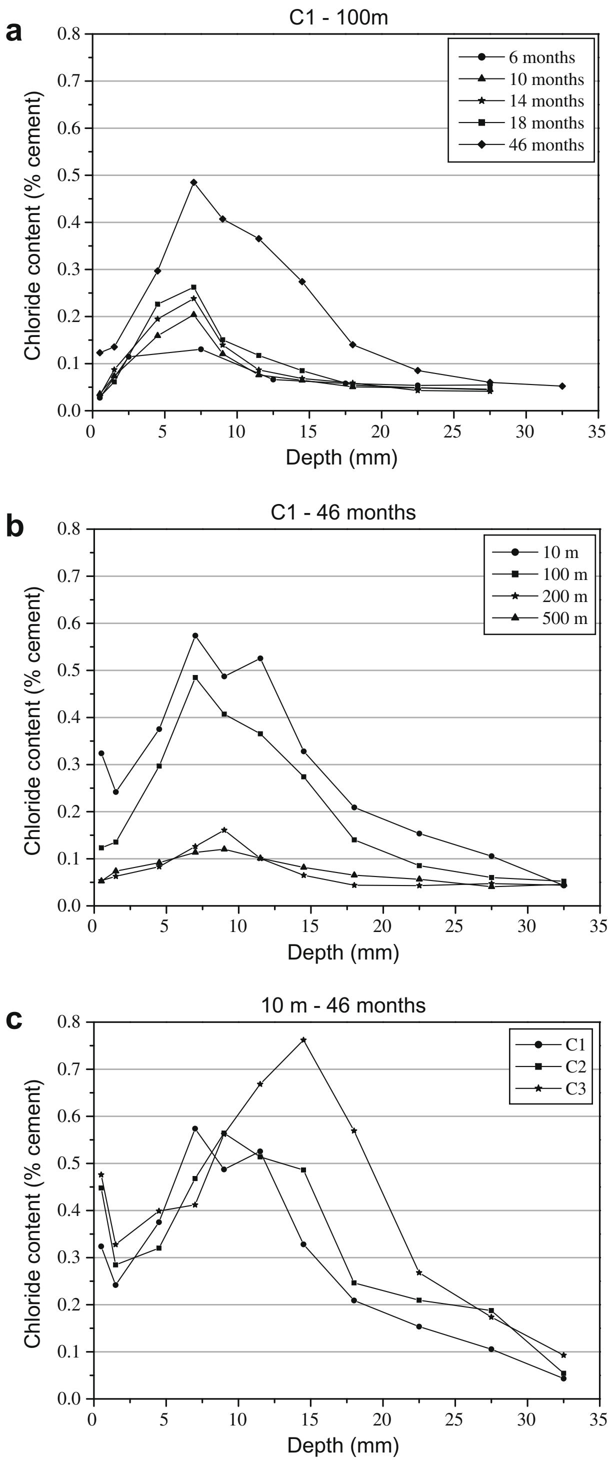

Fig. 5. Chloride profiles in concrete – influence of time (a), distance from the sea/salinity of marine aerosol (b) and characteristics of concrete (c).

aerosol (Fig. 5a). Chloride profiles also show lower chloride penetration into concrete with the distance from the sea, as a consequence of the availability of chlorides in atmosphere at each exposure site (Fig. 5b). A typical decrease in chloride content with w/c decrease is also presented, which is related to materials porosity (Fig. 5c). Profiles behaviour is the basis for the analysis done in the next section, where simulations for 50 years of natural exposure are incorporated.

5. Chloride deposition as an environmental indicator

5.1. Relationship with total chlorides accumulated into concrete

When getting away from the sea, there is a reduction on availability of chlorides in airborne. Thus, there is also a reduction on chloride concentrations in concrete. However, this behaviour does not follow a linear relation between chlorides from marine aerosol and chlorides that penetrate into concrete. This relationship was observed in a previous paper [16] to be represented by the expression $C_{tot} = C_0 + k_d \cdot \sqrt{D_{ac}}$, where C_{tot} is the average of total chlorides accumulated into concrete, C_0 is the initial chloride content in concrete, k_d is a concrete and environmental dependant coefficient and D_{ac} is the accumulated chloride deposition on the wet candle device.

Table 3 presents these relationships to each concrete mixture, which were updated incorporating data up to 46 months. Although they show good agreement with experimental data, they are empiric relationships and, thus, are valid for concretes and environments similar to those worked in this paper. In addition, they consider that there are not important differences among climatic characteristics at monitoring stations. Nevertheless, these expressions are an alternative to represent the relationship between chlorides from marine aerosol and its accumulation into concretes exposed in marine atmosphere zone.

Taking into account that the variable D_{ac} represents the month-to-month sum of all measurements, it is possible to set values of C_{tot} along time knowing the average chloride deposition rates representative of each site analysed. Fig. 6 presents simulations of C_{tot} taking into account environments with different representative chloride deposition rates (D) and 50 years of exposure.

Although the expressions presented in Table 3 were obtained with data of up to 46 months of environmental exposure and this period contributes to improve the accuracy of the expressions obtained in the first stage of this study, the extrapolations

Table 3
Representative equations for $C_{tot} - D_{ac}$ relationship incorporating long-term data.

Concrete	C_0 (% cement)	Equations	r^2	Number of points (n)
C1	0.0465	$C_{tot} = 0.0465 + 0.00781D_{ac}^{0.5}$	0.92	20
C2	0.0456	$C_{tot} = 0.0456 + 0.00873D_{ac}^{0.5}$	0.91	20
C3	0.0401	$C_{tot} = 0.0401 + 0.01080D_{ac}^{0.5}$	0.91	20

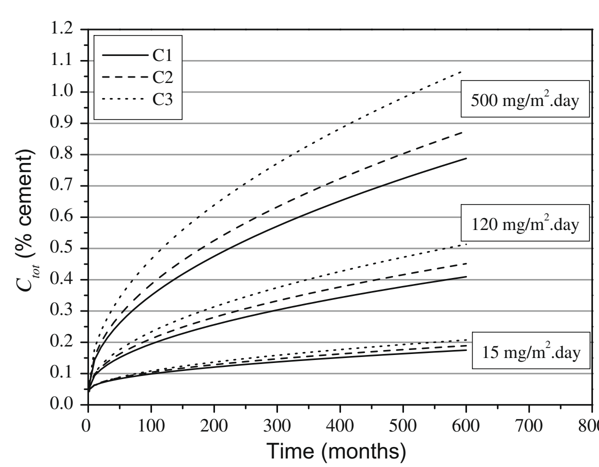

Fig. 6. C_{tot} simulations for concretes C1, C2 and C3, chloride deposition rates of 15, 120 and 500 mg/m^2 day and 50 years of exposure.

presented in Fig. 6 can embody some errors for not incorporating tendencies that may be visible only after even longer observation periods. However, these extrapolations represent a tool to analyse relative behaviour of concrete structures subjected to environments with different chloride deposition rates and thus are a way to indicate relative performances of similar concrete structures exposed at sites with different levels of salinity.

Curves in Fig. 6 show, for concrete C1 and 50 years of exposure, that at sites with 500 mg/m^2 day deposition rate, C_{tot} assume a value more than 4 times higher than that at sites with 15 mg/m^2 day deposition rate and around 2 times higher than that at sites with 120 mg/m^2 day deposition rate. This means that the same concrete has different performances regarding chloride accumulation over time and, despite of depending on other variables, concrete will be less durable, from the point of view of starting corrosion process, at sites with 500 mg/m^2 day deposition rate. This kind of analysis can be assumed as similar for the other concretes and show the applicability of chloride deposition rate as an environmental indicator.

5.2. Relationship with chloride threshold advance in concrete

Another way to set relationships between chloride deposition rate on the wet candle and concrete structures performance is through service-life analysis. This was done here by numeric extrapolations over 50 years of exposure, considering chloride profiles during the first 46 months of exposure, environmental and concrete characteristics influence on chloride transport and 0.4% of cement mass as total chlorides threshold. This chloride threshold has been accepted as the critical chloride content in concrete able to start the corrosion of reinforcement [42,43], as previously commented in Section 2.

All the procedures adopted in these extrapolations are fully detailed elsewhere [39] and are resumed below in three steps, which consider the analysis and rescaling of chloride profiles, the numerical obtaining of transport parameters and numerical extrapolations of profiles behaviour. Here, a stronger emphasis is given to the extrapolations using the obtained relationships.

5.2.1. Analysis and rescaling of chloride profiles

When concrete structures are subjected to wetting and drying cycles, which is the case of concrete structures in marine atmosphere zone, chloride profiles tend to be two-zone profiles, with a maximum chloride concentration a few millimetres inside, as described in Section 2 [24,25].

In accordance with this behaviour, chloride profiles obtained in this study were two-zone profiles with an external zone, where wetting and drying cycles take place and favour to capillary sorption and an inner zone, where the humidity remain at higher levels and the transport of chlorides can be attributed mainly to diffusion, in a similar way as previously suggested in literature [16,23,24,26,39,44] and it is represented in Fig. 7. This is supported by the fact that concrete specimens were exposed in a region with high levels of relative humidity [40] and, consequently, high levels of humidity content in concrete porous network are expected, although stronger variations of humidity content in surface layers of concrete can be observed. This favours to capillary sorption in surface layers and diffusion in inner layers [23,24].

As an alternative, chloride transport into concrete can be analysed considering only the diffusion zone, which takes into account a rescaling of chloride profiles starting from the end of convection zone [3,44] (Fig. 7). Concerning this aspect, only the diffusion zone of chloride profiles was used in the present numeric approach.

Starting with a rescaled profile (Fig. 7) and assuming that the depth of the convective zone does not change along time, which is an approximation to real conditions, the maximum chloride concentration in the interface between convective and diffusion zones ($C_{máx}$), which means the surface chloride content of the rescaled profile, can be represented by Eq. (1), where, C_0 is the initial chloride content in concrete, $k_{cmáx}$ is a material and environmental dependant coefficient and D_{ac} is the accumulated deposition of chlorides on the wet candle [39]. This means that the increase of $C_{máx}$ tends to attenuate along time, in a similar way as C_{tot}. Table 4 resumes the fitting results of Eq. (1), considering the 46 months observation period.

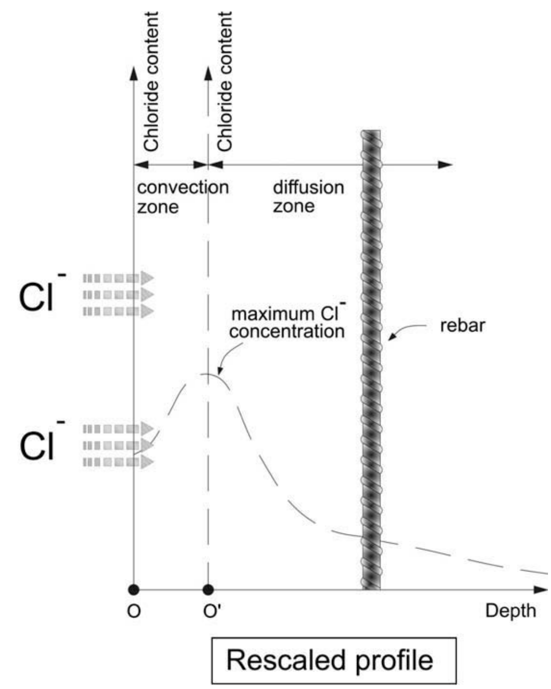

Fig. 7. Schematic representation of rescaling two-zone profiles.

$$C_{máx} = C_0 + k_{cmáx}\sqrt{D_{ac}} \quad (1)$$

5.2.2. Numerical obtaining of transport parameters

Using the finite difference method, least-squares fitting [45] and computational routines, a numerical simultaneous fitting was done to each set of chloride profiles representative of each concrete and exposure station to obtain the parameters of the model: D_0 and m, which are detailed along this section.

Eq. (2) corresponds to the finite difference representation of Fick's second law of diffusion and it is complemented by Eq. (3) that represents the dependence of diffusion coefficient on some influencing variables. In these equations, $C_{i,j}$ is the chloride concentration at the depth i and time j, Δx is the depth variation, Δt is the time variation, D_{ap} is the apparent diffusion coefficient, D_0 is a referential diffusion coefficient and $f(t)$, $f(T)$ and $f(SD)$ represent, respectively, the influence of time, temperature and water saturation degree of concrete on apparent diffusion coefficient [28,29,32,34,46,47].

Table 4
Representative equations for $C_{max} - D_{ac}$ relationship incorporating long-term data.

Concrete	C_0 (% cement)	$k_{cmáx}$(% cement)	Equations	r^2	Number of points (n)
C1	0.0465	0.021	$C_{max} = 0.0465 + 0.021D_{ac}^{0.5}$	0.91	20
C2	0.0456	0.022	$C_{max} = 0.0456 + 0.022D_{ac}^{0.5}$	0.93	20
C3	0.0401	0.029	$C_{max} = 0.0401 + 0.029D_{ac}^{0.5}$	0.94	20

$$C_{i,j+1} = \frac{(C_{i+1,j} - 2C_{i,j} + C_{i-1,j})}{\Delta x^2} \cdot \Delta t \cdot D_{ap} + C_{i,j} \quad (2)$$

$$D_{ap} = D_0 \cdot f(t) \cdot f(T) \cdot f(SD) \quad (3)$$

The influence of temperature was not considered in the present case, due to its low influence on the apparent diffusion coefficient in this specific case. Taking into consideration the variation of average temperature data in the studied region, changes of <2% were observed in the apparent diffusion coefficient. As a result, Eq. (3) can be rewritten as Eq. (4), where t_0 is a reference time (1 s), t is the variable time, m is a time dependant coefficient and SD is the water saturation degree of concrete porous network. The structure of $f(t)$ and $f(SD)$ terms was based on previous works that consider the concrete hydration over time [28,29,46,47] and the influence of water content in concrete porous network in chloride transport [32,34]. The numerical approach is fully described in [39]. The results of the fittings are resumed in Table 5, which include D_0, m and the functions that represent the behaviour of the water saturation degree of concrete over time. These functions represent analytical fittings of Eq. (5) to experimental data of water saturation degree of concrete obtained along the research period, according to the procedures presented in Section 3. In Eq. (5), $SD_{\max}$ and $SD_{\min}$ are, respectively, the maximum and the minimum water saturation degree observed.

$$D_{ap} = D_0 \cdot f(t) \cdot f(SD) \;\Rightarrow\; D_{ap} = D_0 (t_0/t)^m \cdot e^{4.6(SD-1)} \quad (4)$$

$$SD = \frac{SD_{\max} + SD_{\mathrm{mim}}}{2} + \frac{SD_{\max} - SD_{\mathrm{mim}}}{2} \sin\left(2\pi \frac{(t - t_0)}{365}\right) \quad (5)$$

5.2.3. Numerical extrapolations

Starting with the Eq. (1), simulations of $C_{\text{máx}}$ were done, considering average chloride depositions on the wet candle of 500, 120 and 15 mg/m^2 day, which are close to average values for the region studied (10, 100 and 500 m from the sea, respectively). Numeric extrapolations of chloride profiles were done for 50 years also using finite difference method. They were based on parameters obtained thorough the numerical fitting and on $C_{\text{máx}}$ and SD behaviour over time, as well as the average relationship between accumulated chloride deposition on the wet candle and time. From these profile extrapolations, the advance of chloride threshold could be obtained and represented in Fig. 8, taking into account the average chloride deposition rates observed during the experimental study.

Simulations done in Fig. 8 show that, considering service life as the time for chloride threshold to reach reinforcement, it is possible to observe different situations about service life, depending on chloride deposition rate. For example, after 50 years, concrete structures with w/c 0.5 – C1 (Fig. 8a) and located at sites with 15 mg/m^2 day average chloride deposition rate did not present 0.4% of cement mass at any depth. It means that the service life of this structure was not reached for this environmental condition. For sites with 120 mg/m^2 day chloride threshold takes place at 27.5 mm depth and for sites with 500 mg/m^2 day it takes place at 38.0 mm depth, indicating that if reinforcement was placed at

Table 5
Values of D_0 and m from numerical fitting and SD sine functions.

Concrete	Distance from the sea (m)	D_0 ($\times 10^{-6}$ cm^2/s)	m	SD functions	r^2
C1	10	6.28	0.31	$SD = 70.54 + 2.61 \sin(\alpha)$	0.60
	100	7.40	0.34	$SD = 71.31 + 3.41 \sin(\alpha)$	0.63
	200	7.27	0.34	$SD = 70.80 + 5.25 \sin(\alpha)$	0.61
	500	5.03	0.29	$SD = 68.71 + 7.09 \sin(\alpha)$	0.82
C2	10	10.73	0.33	$SD = 67.76 + 3.91 \sin(\alpha)$	0.58
	100	8.69	0.33	$SD = 64.93 + 4.35 \sin(\alpha)$	0.71
	200	7.83	0.29	$SD = 64.58 + 5.55 \sin(\alpha)$	0.75
	500	5.74	0.29	$SD = 68.11 + 8.07 \sin(\alpha)$	0.76
C3	10	12.64	0.32	$SD = 63.54 + 3.27 \sin(\alpha)$	0.57
	100	11.91	0.29	$SD = 64.14 + 7.49 \sin(\alpha)$	0.63
	200	11.64	0.33	$SD = 62.34 + 8.26 \sin(\alpha)$	0.60
	500	8.05	0.27	$SD = 65.28 + 8.68 \sin(\alpha)$	0.71

$\alpha = 2\pi \frac{t - t_0}{365}$.

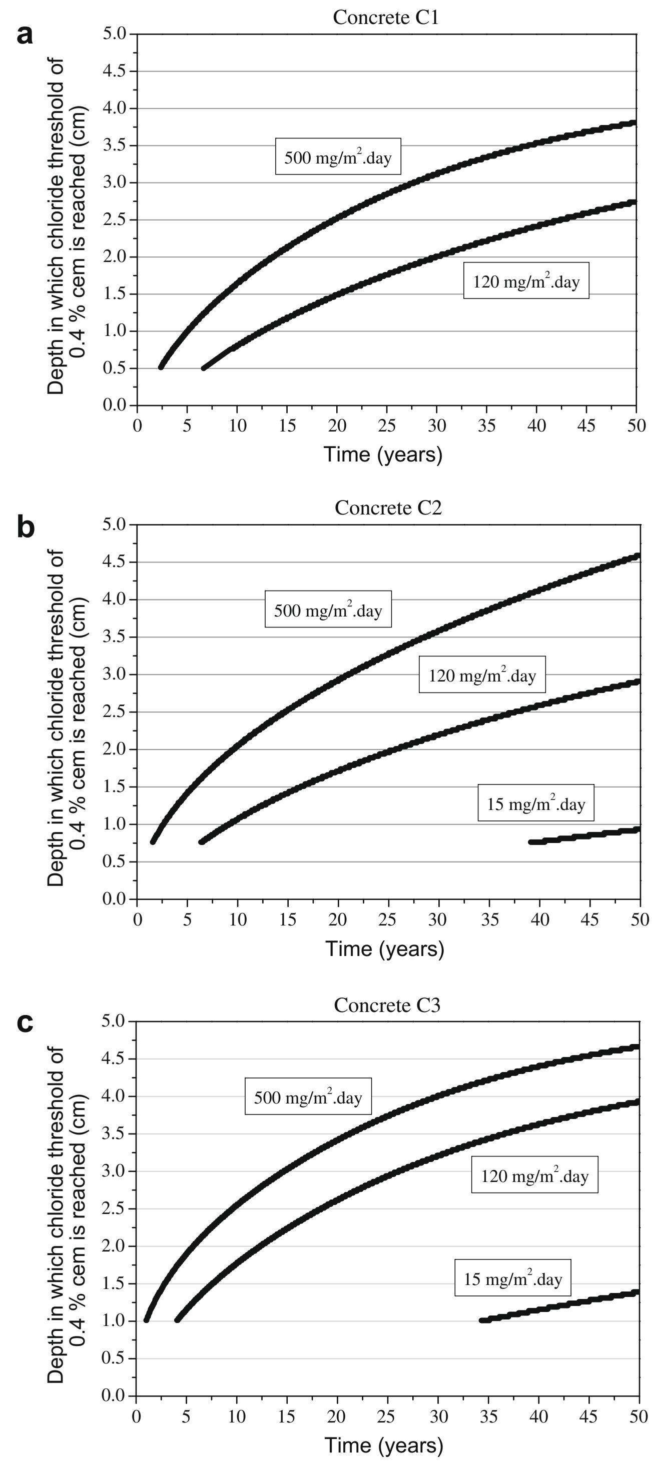

Fig. 8. Simulations of chloride threshold advance in concretes C1 (a), C2 (b) and C3 (c) for different chloride deposition levels.

Table 6
Different combinations of concrete characteristics to reach 50 years service life at environments with distinct chloride deposition levels.

Chloride deposition level (mg/m^2 day)	Concrete	w/c	Minimum concrete cover depth (mm)
500	C1	0.50	38
	C2	0.57	46
	C3	0.65	47
120	C1	0.50	27.5
	C2	0.57	29
	C3	0.65	39
15	C1	0.50	–
	C2	0.57	9
	C3	0.65	13.5

30 mm depth, structures subjected to 500 mg/m^2 day had already reached their service life (almost 28 years). For concretes with *w/c* 0.57 – C2 (Fig. 8b), these depths after 50 years were 9.0, 29.0 and 46.0 mm, respectively, which indicates that more than 45 mm of reinforcement cover are necessary for concrete C2 to reach a service life close to 50 years at sites with 500 mg/m^2 day chloride deposition. A similar analysis can also be done for concrete C3 (Fig. 8c), which shows the highest depths of chloride threshold and, consequently, the lowest service life for a same concrete cover of reinforcement.

Chloride penetration into concrete in marine atmosphere zone, despite its dependence on other environmental and material parameters, is closely related to the availability of chlorides in atmosphere. This way, simulations done here show that chloride deposition rate on the wet candle device can be used as an environmental indicator for concrete durability study in marine atmosphere zone, helping to set minimum durability requirements to concrete structures depending on the deposition level expected, like *w/c* ratio and concrete cover of reinforcement.

For the studied region, the reference of distinct chloride deposition levels on the wet candle lead to different combinations of *w/c* ratios and concrete cover requirements, considering 50 years service life, as exemplified in Table 6.

6. Conclusions

Marine atmosphere zone is characterized by a strong decrease in chlorides presence in the first land areas away from the sea. Considering that chlorides present in atmosphere represent the availability of chlorides to deposit on concrete surface and penetrate into bulk concrete, the relationship between chlorides deposited on the wet candle device and chlorides accumulated into concrete can be a basis for previewing chloride penetration into concrete, taking into account different levels of chloride deposition rates and characteristics of the materials. This was proposed in a previous paper [16] by the relationship $C_{tot} = C_0 + k_d \cdot \sqrt{D_{ac}}$ and confirmed in the current one when incorporating 46 month data.

The use of chloride deposition on the wet candle as an environmental indicator for service-life analysis can be done thorough simulated curves of chloride threshold advance for each level of chloride deposition on the wet candle. From an expected chloride deposition level for a given environment and the characteristic curves of chloride threshold advance for each concrete it is possible to preview the expectancy of service life for different concrete structures, considering different concrete covers or, in another way, to suggest a minimum concrete cover depth for a required time of service life.

Regarding the environment where this research took place and taking as reference a 30 mm concrete cover, service life can vary between 30% and 60% if the same concrete is in a marine atmosphere zone with 120 mg/m^2 day or with 500 mg/m^2 day, which represents an increase of more than four times on chloride deposition. This means that, although service life and chloride deposition vary in opposite ways, this does not take place in the same proportion and thus, this should be taken into account in this kind of analysis.

Furthermore, regarding a service life of 50 years, the required concrete cover can vary between 21% and 59%, for the same previous variation of chloride deposition. As a consequence, concrete structures in marine atmosphere zone should have different durability requirements depending on the chloride deposition level expected.

This way, the chloride deposition on the wet candle, with the advantage of being the result of an easy operation technique, plays an important role as an environmental indicator on service-life analysis of concrete structures in marine atmosphere zone, without the invalidation of other material and environmental influences on chloride penetration into concrete.

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