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RESEARCH ARTICLE

Probabilistic Analysis of the Service Life of Concrete with Recycled Aggregates in Marine Environments

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ABSTRACT

In marine environments, the main cause of degradation of reinforced concrete structures is corrosion induced by the penetration of chloride ions. Durability design approaches have gradually evolved toward performance-based approaches, which are capable of more accurately assessing the behavior of structures over time and their resistance under specific environmental exposure conditions. Due to the high variability of the parameters affecting the durability of these structures, a probabilistic performance-based approach tends to provide results closer to reality by considering the uncertainties of materials and degradation phenomena as random variables. In this work, a probabilistic service life analysis is carried out for concretes produced with RCA from the precast industry at different replacement levels under marine environment exposure conditions. The non-steady-state chloride diffusion coefficient was obtained using the Multi-Regime Method (Asociación Española de Normalização, 2012) and subsequently used as an input parameter in the analyses. The Duracon model was used to estimate the probability of failure of these structures over time, considering a 100-year analysis period and different values of concrete cover, temperature, and environmental aggressiveness levels. The service life estimation was performed considering a target failure probability of 10%.

Keywords: Concrete, Civil construction waste, Recycled concrete aggregate, Marine environment, Chloride diffusion coefficient, Probabilistic performance-based approach, Durability

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1. Introduction

The increasing number of concrete structures showing premature deterioration on a global scale, mainly due to reinforcement corrosion, has driven the development of more robust methods for the design and specification of concrete durability. In this scenario, a continuous evolution of traditional design approaches is observed, with the progressive adoption of performance-based methodologies in

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place of strictly prescriptive criteria (Beushausen & Fernandez Luco, 2016; Wally et al., 2022).

The performance-based approach consists of the direct evaluation of concrete properties and its durability potential as a function of a specific exposure environment. Unlike the prescriptive method, which establishes fixed limits for parameters such as water/binder ratio and minimum cement content, this approach is based on the material's actual capacity to resist degradation mechanisms. This resistance is quantified through durability indicators associated with service life prediction models. Furthermore, this approach integrates essential parameters such as exposure class, design service life, and maintenance plans, allowing for greater technical flexibility, the incorporation of innovative mixes, and the use of more sustainable solutions, while simultaneously seeking to ensure structural safety and reduce costs with premature interventions (Ribeiro, 2018; Meerssche, 2025; Wally et al., 2020).

Within this context, the probabilistic performance-based approach represents a more advanced level of analysis, especially indicated for structures with a design service life equal to or greater than 100 years. Unlike deterministic models, this methodology explicitly considers the uncertainties associated with materials, degradation processes, and environmental conditions, treating input parameters as random variables described by probability distributions. Thus, it becomes possible to estimate the risk of deterioration over time and obtain more realistic predictions of the probability of structural failure, particularly in highly aggressive environments (Ribeiro, 2018; Meerssche, 2025; Zhang et al., 2021).

Simultaneously, the construction industry faces an increasing demand for sustainability, motivated by high consumption of natural resources, intensive energy use, and the environmental impacts associated with the sector (World Green Building Council, 2023). Among the main strategies adopted are the extension of the service life of structures, the reuse and recycling of construction and demolition waste, as well as the use of mineral admixtures and supplementary cementitious materials (Abbas, 2025; Xiao, 2018).

The growing use of concretes with innovative compositions, incorporating supplementary cementitious materials and recycled aggregates, reinforces the relevance of performance-based approaches for durability design. These methodologies use durability indicators directly related to the mass transport mechanisms in concrete, which govern the degradation processes of structures, especially in aggressive environments (Baroghel-Bouny et al., 2009; Ribeiro, 2018).

Among these mechanisms, chloride ion penetration is particularly critical, as it is associated with reinforcement corrosion. Although chloride transport in concrete involves complex phenomena—such as diffusion, capillary absorption, convection, migration, and physical and chemical binding—most existing models consider diffusion as the main entry mechanism for these ions into the material's porous structure (Beushausen & Fernandez Luco, 2016; Wally et al., 2022; Lopes et al., 2022a, 2022b).

Concrete resistance to chloride penetration can be experimentally evaluated using the steady-state diffusion coefficient and the non-steady-state diffusion coefficient. The former characterizes transport under constant flow conditions, while the latter represents a global parameter that simultaneously incorporates the transport and retention of chlorides by the solid phases of the cement paste. Both are widely used as durability indicators and as input parameters in probabilistic service life analyses (Asociación Española de Normalização, 2012; Wally et al., 2021).

In the scope of sustainability, recycled concrete aggregates (RCA) have been widely investigated as an alternative to natural aggregates, with significant advances in recent decades. However, relevant gaps still persist regarding mix design and, mainly, the durability of structural concrete produced with these materials (Xiao, 2018). The primary technical limitations of RCA stem from the presence of adhered residual mortar, which increases the porosity of the aggregate and weakens the interfacial transition zones (Aguilar & Mendoza, 2007; Salles et al., 2021).

Studies indicate that the performance of recycled concrete strongly depends on the quality of the original concrete, the production method of the recycled aggregate, and the replacement level adopted (Pimentel et al., 2020; Salles et al., 2021). Although the reduction in mechanical properties is generally proportional to the increase in the replacement level (Prasittisopin et al., 2025), several studies point out that replacements between 30% and 50% can be technically viable for structural applications (Arredondo-Rea et al., 2019; Mahmood et al., 2022; Nanya et al., 2021). More recently, Lu (2024) suggested that a replacement level of 20% represents a suitable balance between technical performance and regulatory compliance. Studies, such as those by Zhu et al. (2019, 2020), indicate that concrete using recycled aggregates can achieve a service life of at least 50 years, even when exposed to aggressive environments.

Despite these advances, the durability of recycled concrete in aggressive environments, especially regarding chloride penetration, remains one of the main challenges. The high heterogeneity of waste and the absence of robust statistical models or sufficiently precise formulations hinder reliable service life estimation for these structures (Thomas et al., 2013; Yu & Lin, 2020). Although recent studies

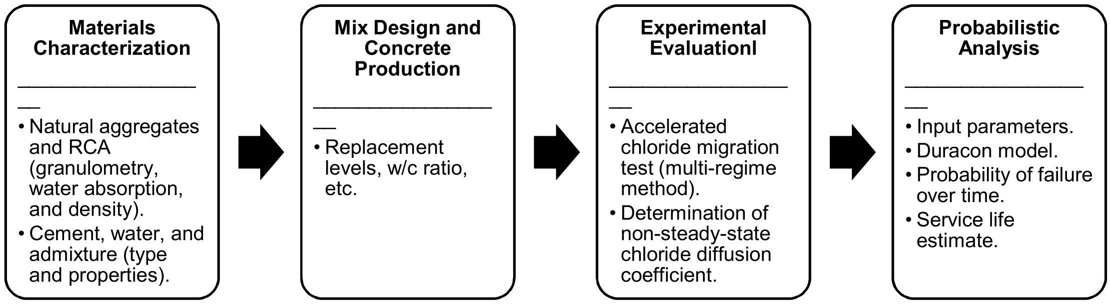

Fig. 2.1. Flowchart of the research methodology illustrating the stages from material characterization to the probabilistic service life assessment.

point to the potential of emerging techniques, such as machine learning and aggregate surface treatments, to mitigate these risks (Wang et al., 2024; Zhao et al., 2024), there is still a significant demand for research that integrates optimized mix design methods with long-term performance analyses under severe exposure conditions.

In this context, the present work carries out a probabilistic service life analysis of concretes produced with different replacement levels of natural aggregates by recycled concrete aggregates. The chloride diffusion coefficient, obtained by the Multi-Regime Method, was adopted as an input parameter in the analyses. The evaluation of the failure probability was conducted using the Duracon model, considering exposure conditions in a marine environment. Additionally, the effects of concrete cover, temperature, and environmental aggressiveness on the service life estimates of the structures were analyzed.

1.1. Scope

This research is subject to the following technical constraints: (i) the replacement levels of natural coarse aggregate by recycled concrete aggregate are limited to 20%, 50%, 75%, and 100%; (ii) the concrete mixtures were produced with w/c ratios between 0.39 and 0.41; (iii) chloride penetration was evaluated solely through accelerated testing; and (iv) the recycled aggregates originated from a single source of discarded precast concrete elements. Furthermore, the probabilistic service life modeling focuses exclusively on the corrosion initiation stage, disregarding the propagation phase.

2. Methodology

To provide a clear overview of the experimental campaign and the analytical procedures, Fig. 2.1 illustrates the sequential stages and inter-relationships of the methods employed in this study.

The probabilistic service life analysis was performed using the Duracon software, a specialized tool designed for the reliability-based durability design of concrete structures exposed to chloride environments. The software functions by modeling chloride ingress based on Fick's Second Law of Diffusion, incorporating the environmental and material parameters. Its primary purpose is to calculate the probability of failure over time, considering the statistical variability of input variables such as concrete cover, surface chloride concentration, and the diffusion coefficient.

2.1. Materials used

For the production of the concretes used in this study, a Portland Composite Cement (CPC 40) commercially available in Uruguay was used. The properties of this cement meet the requirements established by the UNIT 20 standard (Instituto Uruguayo de Normas Técnicas, 2022). According to the manufacturer's catalog, this cement contains small amounts of gypsum, limestone filler, and pozzolan in its mixture.

Potable water supplied by the local distributor was used. When necessary, a superplasticizer admixture was used with the objective of improving the workability of the concretes and maintaining a fixed water/cement (w/c) ratio. This admixture has a specific gravity of 1.1 g/cm^3. The adopted dosage was 0.85% in relation to the cement mass.

As fine aggregates, sands of different granulometries were used. The fine sand is from Ciudad del Plata, Department of San José, Uruguay. The coarse sand is from Paso de Pache, Department of Canelones, Uruguay.

As coarse aggregates, natural gravel and Recycled Concrete Aggregate (RCA) were used. The natural gravel is from Las Piedras, Department of Canelones, Uruguay. It is a stone widely used in the south of the country, found in quarries with a certain degree of disintegration, requiring only granulometric classification and washing. Although it is considered a

Table 2.1. Proportion of concrete mixtures used in the experimental studies.

Mixture	w/c ratio	Cement [kg/m^3]	Fine sand [kg/m^3]	Coarse sand [kg/m^3]	Natural gravel [kg/m^3]	RCA [kg/m^3]
REF	0.39	410	343.34	516.66	952.65	0.00
20 HR	0.39	410	343.34	516.66	762.12	169.39
50 HR	0.41	410	341.64	511.51	469.72	415.98
75 HR	0.41	410	341.64	511.51	234.86	623.97
100 HR	0.41	410	344.90	510.01	0.00	838.56

good aggregate, due to this characteristic, it is not commonly used for very high-strength concretes, with its usual application in concretes up to 40 MPa.

The Recycled Concrete Aggregate (RCA), in turn, was obtained from the crushing of a single type of concrete, from precast elements that were discarded by a precast industry. The processing of this material was carried out by the company RCD *Reciclaje*, located in Montevideo, Department of Montevideo, Uruguay.

2.2. Evaluated concrete mixtures

All mixtures were proportioned based on the method of the Argentine Portland Cement Institute (ICPA), with a target slump value of 120 ± 10 mm. Table 2.1 presents the nomenclature adopted: “REF” refers to the reference mixture, while the other mixes are identified by the percentage of substitution of natural aggregate by recycled aggregate (20%, 50%, 75%, and 100%), followed by the term “HR” (*Hormigón Reciclado*). The experimental data presented in this study were originally obtained and described by Meerssche (2025).

For each concrete mix, 3 cylindrical specimens were cast, with dimensions of 100 mm in diameter and 200 mm in height. The concreting was carried out in accordance with the UNIT-NM 79 standard (Instituto Uruguayo de Normas Técnicas, 1998) and the molding according to UNIT-ISO 1920-3 (Instituto Uruguayo de Normas Técnicas, 2019). For the determination of the chloride diffusion coefficients, the specimens were sectioned into five 30 mm thick samples, with an initial discard of 25 mm from the ends of the specimen.

2.3. Determination of the chloride diffusion coefficient

The test method described in the UNE 83987 standard (Asociación Española de Normalização, 2012) was used to determine the chloride diffusion coefficient in non-steady state. It consists of an accelerated method, denominated the Multi-Regime Method. For each concrete mix, 3 fully saturated specimens were used in the tests, which were performed at 91 days of age.

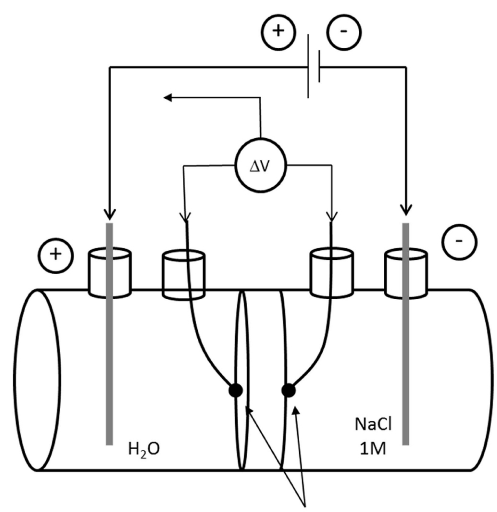

Fig. 2.2. Schematic representation of the test for determining chloride diffusion coefficients. Source: Adapted from UNE 83987 (Asociación Española de Normalização, 2012).

In this test method, the concrete specimen is positioned between two solutions: the catholyte, containing the chloride ions and the negative electrode (cathode), and the anolyte, containing only distilled or deionized water and the positive electrode (anode). By applying a potential difference of 12 V across the concrete specimen, the chloride ions are attracted to the positive electrode and migrate towards it, passing through the specimen. The increase in chloride concentration in the anolyte is measured by determining its electrical conductivity. The test setup schematic is presented in Fig. 2.2.

The evolution of conductivity in the anodic compartment follows a trend that is divided into 3 distinct stages, as shown in Fig. 2.3. In general, two weeks are sufficient to obtain the results.

Electrical conductivity is a parameter that depends on temperature; thus, in the absence of a conductivity cell with automatic correction of the obtained values, these must be corrected. The correction of electrical conductivity to the reference temperature is performed according to the Spanish standard UNE 83987 (Asociación Española de Normalização, 2012), as shown in Eq. (2.1).

$$c_{25} = c_T + 0,0217 \cdot (25 - T) \cdot c_T \tag{2.1}$$

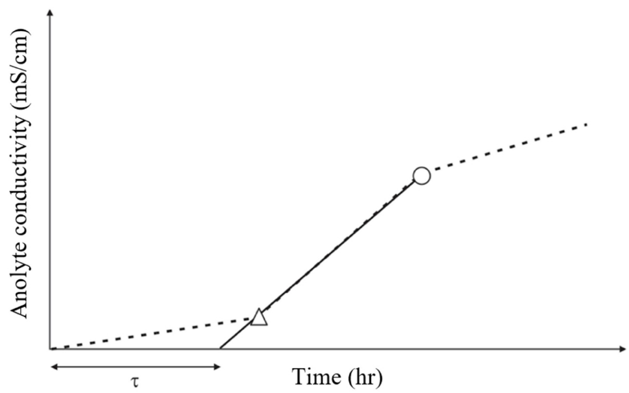

Fig. 2.3. Schematic representation of the evolution of conductivity, as well as the time lag (τ); start (Δ) and end ($\circ$) of the steady-state. Source: Adapted from Ribeiro (2018).

Where c_{25} is the electrical conductivity obtained at 25°C [mS/cm], c_T is the electrical conductivity obtained at temperature T (°C) [mS/cm], and T is the temperature [°C].

The quantity of chlorides in the anolyte, based on the conductivity values at the reference temperature, is calculated using Eq. (2.2), also following the procedures defined in UNE 83987 (Asociación Española de Normalização, 2012):

$$Cl^- = 1 \cdot 10^{-3} \cdot [-1,71 + (11,45 \cdot c_{25})] \cdot V_a \tag{2.2}$$

Where Cl^- is the quantity of chlorides [mol], c_{25} is the electrical conductivity obtained at 25°C [mS/cm], and V_a is the volume of the anolyte [L].

The non-steady-state chloride diffusion coefficient is determined from Eq. (2.3), as prescribed by UNE 83987 (Asociación Española de Normalização, 2012):

$$D_{ns} = \frac{e^2}{2 \cdot \tau \cdot \varphi} \tag{2.3}$$

Where D_{ns} is the non-steady-state chloride diffusion coefficient [cm^2/s], e is the thickness of the specimen [cm], τ is the time lag [s], and φ is the acceleration factor of the electric field [V/cm], obtained by Eq. (2.4).

$$\varphi = \frac{z \cdot F}{R \cdot T_A} \cdot \Delta\phi \tag{2.4}$$

Where z is the valence of the chloride ion [1], F is the Faraday constant [23060 cal/Veq], R is the gas constant [1.9872 cal/mol·K], T_A is the average temperature of the anolyte during the test [K], and $\Delta\phi$ is the normalized electric field [V/cm], obtained by Eq. (2.5).

$$\Delta\phi = \frac{\Delta E}{e} \tag{2.5}$$

Where ΔE is the average of the effective voltages measured on both faces of the specimen, during the non-steady-state period [V] and e is the thickness of the specimen [cm].

2.4. Model for estimating chloride penetration

The Duracon model, presented by Gjørv (2014), was developed for the durability analysis of reinforced concrete structures in aggressive environments and can be used for both durability design and for assessing the maintenance needs of structures during their service life. The calculation of the corrosion probability is based on the modified Fick's law of diffusion, in combination with a Monte Carlo Simulation (Gjørv, 2014; PIANC, 2010).

The rate of chloride ingress was estimated using Fick's second law of diffusion, as proposed by Collepardi et al. (1970, 1972) and presented by Gjørv (2014), according to Eq. (2.6):

$$C_{(x,t)} = C_S \cdot \left[1 - erf\left(\frac{x_C}{2 \cdot \sqrt{D(t) \cdot t}}\right)\right] \tag{2.6}$$

Where $C_{(x,t)}$ is the chloride concentration at depth x_C after a time t [%/mass of cement], C_S is the chloride concentration on the concrete surface [%/mass of cement], erf is the Gauss error function, $D(t)$ is the chloride diffusion coefficient in the concrete [m^2/s], and x_C is the distance from the edge of the member where the critical chloride concentration C_{cr} occurs [mm].

The time-dependent chloride diffusion coefficient is obtained via Eq. (2.7), following Takewaka and Mastumoto (1988) and Tang and Gulikers (2007), as described by Gjørv (2014).

$$D(t) = \frac{D_0}{1-\alpha} \cdot \left[\left(1 + \frac{t'}{t}\right)^{1-\alpha} - \left(\frac{t'}{t}\right)^{1-\alpha}\right] \cdot \left(\frac{t_0}{t}\right)^{\alpha} \cdot k_e \tag{2.7}$$

Where D_0 is the diffusion coefficient determined at the reference time [m^2/s], t' is the age of the concrete when exposed to ions [years], α is the concrete aging factor, and k_e is a parameter that introduces the influence of temperature on the diffusion process, obtained by Eq. (2.8), according to Kong et al. (2002) and described by Gjørv (2014).

$$k_e = exp\left[\frac{E_A}{R} \cdot \left(\frac{1}{293} - \frac{1}{273 + T}\right)\right] \tag{2.8}$$

Where exp is the exponential function, E_A is the activation energy of chloride diffusion [kJ/mol], R is

Table 2.2. Input parameters for the durability analyses.

Input parameter	Unit	Distribution type	Mean value	Standard deviation
C_{cr}	% by weight of cement	Normal	0.4	0.1
C_S	% by weight of cement	Normal	5.5	1.3
			3.5	0.8
			1.5	0.5
x_C	mm	Normal	40	4.0
			50	5.0
D_0	$10^{-12} \cdot m^2/s$	Normal	2.63 [a]	0.263 [a]
			2.10 [b]	0.210 [b]
			3.16 [c]	0.316 [c]
			3.94 [d]	0.394 [d]
			3.16 [e]	0.316 [e]
T	°C	Deterministic	10	-
			20	
			30	
t_0	days	Deterministic	91	-
t'	days	Deterministic	91	-
α	-	Normal	0.4	0.08

a = REF; b = 20 HR; c = 50 HR; d = 75 HR; e = 100 HR.

the universal gas constant [J/(mol·K)], and T is the temperature [°C].

Based on this model, the limit state function shown in Eq. (2.9) is established following Wally et al. (2022).

$$g(x,t) = C_{cr} - C_{(x,t)} \tag{2.9}$$

When $g(x,t) > 0$, the structure is safe regarding the depassivation limit state; on the other hand, when $g(x,t) \leq 0$, the structure has reached the reinforcement depassivation limit state, configuring a failure situation. The failure probability p_f is defined as the probability of reaching the reinforcement depassivation limit state, as expressed in Eq. (2.10) according to Wally et al. (2022).

$$p_f = P\left(C_{(x,t)} \geq C_{cr}\right) \tag{2.10}$$

2.5. Input parameters for durability analysis

The diffusion coefficients, obtained as presented in Section 2.3, were used as input parameters in the durability analyses, and the results are presented in Table 2.2. The use of the diffusion coefficient measured at early ages as an input parameter is a safety factor, considering that diffusivity tends to decrease over time (Wally et al., 2022).

The concrete cover used in the analyses follows the recommendations of NBR 6118 (ABNT, 2023) for Environmental Aggressiveness Classes (CAA) III and IV, corresponding to the marine environment and the splash zone, respectively.

The critical chloride concentration adopted follows the general guidelines of Gjørv (2014). Three distinct values of surface chloride concentration were considered, corresponding to moderate, medium, and high levels of environmental load.

Three distinct temperature ranges were adopted in the analysis. The aging factor of concrete follows the general guidelines of Gjørv (2014), considering that the concretes were produced with Portland cement.

10^6 simulations were performed using Duracon software. The probability of failure was calculated year by year, for an analysis period of 100 years. The reference time and the age of the concrete when exposed to ions were adopted as 91 days, the age at which the diffusion coefficients were determined. The input parameters used in the analyses are presented in Table 2.2.

A probability of failure equal to 10% was adopted as the limit criterion for estimating the service life of structures. It is important to highlight that there is no consensus in the literature on this limit value. Helland (2013) reports that Norway adopted a value of 10% for the calibration of standardized prescriptive parameters. However, according to the author, other European countries have adopted values of 2%, 30%, and 50%.

It is important to highlight that the REF and 20 HR mixes have lower water/cement (w/c) ratios than the other mixes evaluated (Table 2.1). Although specific tests to determine porosity were not performed in this study, it is established in the literature that increasing the w/c ratio increases the porosity of the cement paste. This factor directly impacts both the mechanical performance and the durability of concrete, as it is associated with the ease of penetration of aggressive agents.

Another relevant aspect is related to the chloride diffusion coefficient in the non-steady state of the mixes with 50% and 100% substitution, whose results were identical. Both mixes presented the same time

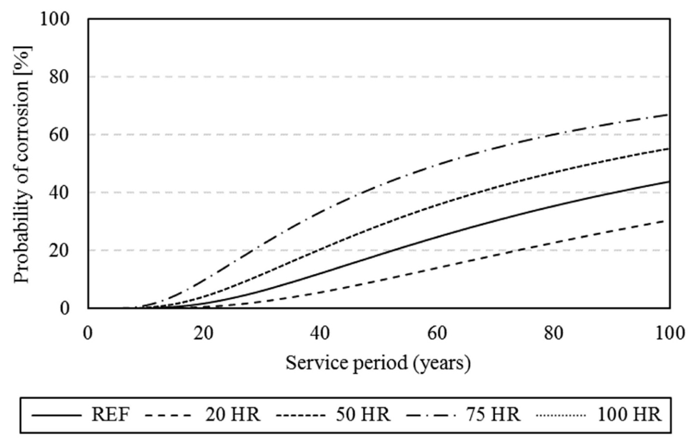

Fig. 3.1. Effect of concrete cover on the probability of corrosion for $x_C = 40$ mm.

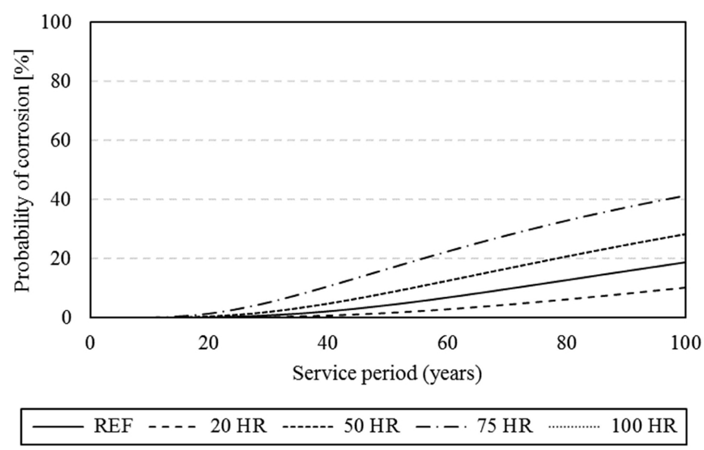

Fig. 3.2. Effect of concrete cover on the probability of corrosion for $x_C = 50$ mm.

lag when evaluated by the Multi-Regime Method. This parameter defines the time required, from the beginning of the test, for a constant flow of chloride ions to be established from the catholyte to the anolyte. This result may be associated with the heterogeneity of the recycled aggregates. It is important to emphasize that the estimates for both mixes will be identical due to this factor.

Table 3.1. Results of service life estimation considering the effect of concrete cover.

Service life estimation [years]		
	Concrete cover [mm]	
Mix	40	50
REF	36.51	70.74
20 HR	50.95	98.77
50 HR	27.82	53.88
75 HR	20.10	38.85
100 HR	27.82	53.88

3. Results and discussion

3.1. Effect of concrete cover

In order to analyze the effect of concrete cover, simulations were performed considering thicknesses of 40 mm and 50 mm, with the following exposure scenarios: $C_S = 1.5\%$ by mass of cement and $T = 10$ °C. The results of the durability analyses are presented in Figs. 3.3 to 3.5. Table 3.1 shows the results of service life estimations.

The results presented in Table 3.1 highlight the critical role of concrete cover thickness as a primary physical barrier against chloride-induced corrosion. As expected, an increase in cover depth significantly extends the predicted service life by increasing the path that chloride ions must traverse to reach the reinforcement.

As can be seen in Table 3.1, with an increase in concrete cover thickness from 40 mm to 50 mm, the reference concrete (REF) would have an increase in service life from approximately 36.51 years to 70.74 years. On average, the concrete mixes showed an

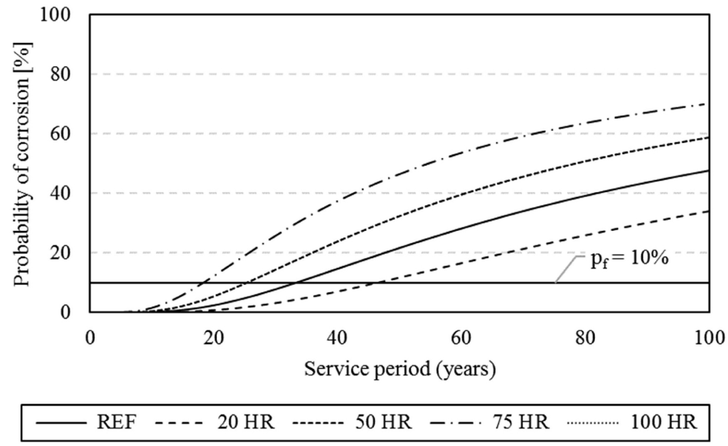

Fig. 3.3. Effect of environmental aggressiveness on the probability of corrosion for $C_S = 1.5\%$.

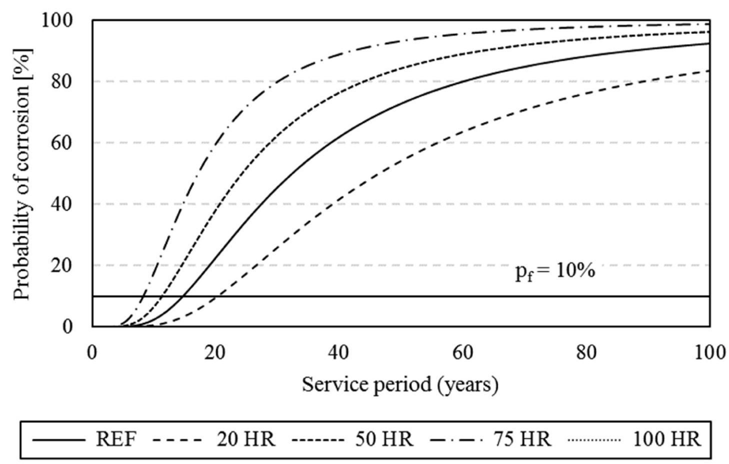

Fig. 3.4. Effect of environmental aggressiveness on the probability of corrosion for $C_S = 3.5\%$.

increase in estimated service life of approximately 94% with an increase of only 10 mm in cover.

The mix with 20% replacement (20 HR) showed the best estimates, with a 40% increase compared to REF. On the other hand, the 50 HR and 100 HR mixes showed reductions of around 24%, and the 75 HR mix showed the worst performance with approximately a 45% reduction in estimated service life.

3.2. Effect of environmental aggressiveness

In order to analyze the effect of environmental aggressiveness, simulations were carried out considering surface chloride concentrations of 1.5, 3.5 and 5.5% by mass of cement, keeping the following parameters constant: $x_C = 50$ mm and $T = 20$ °C. The results of the durability analyses are presented in Fig. 3.2. Table 3.2 shows the results of service life estimations.

The service life results presented in Table 3.2 demonstrate that environmental aggressiveness is a critical factor in durability. Since the chloride loading is directly influenced by local exposure conditions, the significant reduction in the predicted years for the most severe scenarios reflects the cumulative effect of chloride ingress over time. To ensure accuracy in these predictions, the estimation and selection of an appropriate surface chloride concentration should ideally be based on local field investigations

Table 3.2. Results of service life estimation considering the effect of environmental aggressiveness.

	Service life estimation [years]		
	Chloride loading [% by mass of cement]		
Mix	Moderate	Average	High
	1.5	3.5	5.5
REF	33.33	14.66	10.50
20 HR	46.52	20.29	14.49
50 HR	25.41	11.27	8.10
75 HR	18.36	8.22	5.93
100 HR	25.41	11.27	8.10

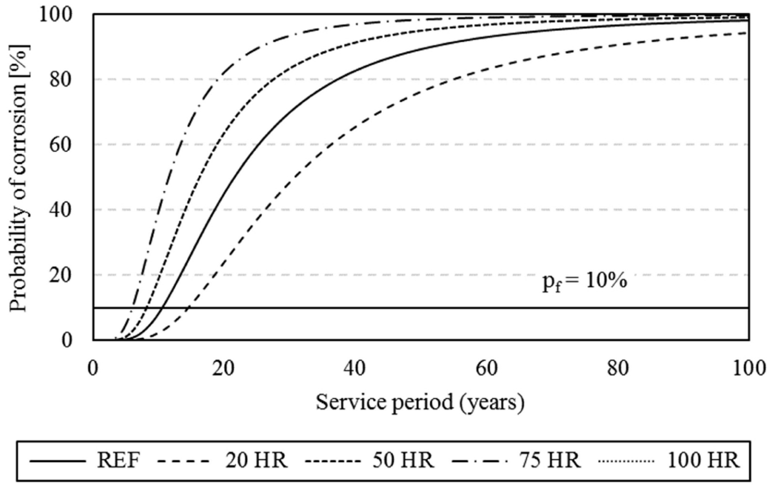

Fig. 3.5. Effect of environmental aggressiveness on the probability of corrosion for $C_S = 5.5\%$.

of similar structures in similar environments. In the absence of such data, general guidelines from the literature can be used to select representative values for the most critical parts of the structure, accounting for the high scatter and variability inherent to marine exposure.

In relation to the reference concrete (REF), for an average chloride load, the 20 HR concrete showed an increase of approximately 38% in the service life estimate. On the other hand, the 50 HR and 100 HR mixes showed reductions of 23%, while the 75 HR mix had the worst performance, with a reduction of around 44%. It is also observed that, with only a 2% increase in surface chloride concentration, the service life estimate can be reduced by 28% to 56%. Similar results were reported by Amorim Júnior et al. (2019), who also observed, through simulations performed in the Duracon software, a significant reduction in the service life estimate of concrete as natural coarse aggregate is replaced by recycled aggregate.

It is also observed that the level of aggregate substitution in the service life estimate showed a non-linear behavior. In all simulated scenarios, the mix with 20% substitution obtained a performance superior to the reference concrete.

This behavior, where a low content of recycled aggregate can present improved durability, has already been observed in the literature. Salles et al. (2021) also noted an improvement in carbonation resistance with the use of recycled aggregate, although they also observed mechanical losses. Similarly, Otsuki et al. (2003) demonstrated that recycled concretes with chloride penetration resistance superior to that of conventional concrete can be obtained through the refinement of the new interfacial transition zone (ITZ). It is possible that 20% recycled aggregate generated a microstructural optimization effect.

Table 3.3. Results of service life estimation considering the effect of temperature.

Service life estimation [years]			
	Temperature [°C]		
Mix	10	20	30
REF	16.03	7.74	3.99
20 HR	22.17	10.67	5.43
50 HR	12.30	5.98	3.08
75 HR	8.98	4.36	2.24
100 HR	12.30	5.98	3.08

3.3. Effect of temperature

To analyze the effect of temperature, simulations were performed considering temperatures of 10, 20, and 30 °C, keeping the following parameters constant: $x_C = 40$ mm and $C_S = 3.5\%$ by mass of cement. The results of the durability analyses are presented in Figs. 3.6 to 3.8. Table 3.3 shows the results of service life estimations.

As expected, all concrete mixes showed significant reductions in service life predictions with increasing temperature, highlighting the importance of this parameter in durability analyses. Temperature is a determining factor for chloride ion diffusion in concrete, as it affects transport mechanisms and the rate of chemical reactions. Essentially, thermal increase accelerates transport processes, intensifying the penetration of aggressive agents and thereby anticipating the onset of reinforcement corrosion.

It is observed that, in relation to REF concrete, at a temperature of 20°C, the 20 HR mix showed an increase of approximately 38% in the estimated service life, while the 50 HR and 100 HR mixes had reductions of 23%, and the 75 HR mix showed the largest decrease, of about 44%.

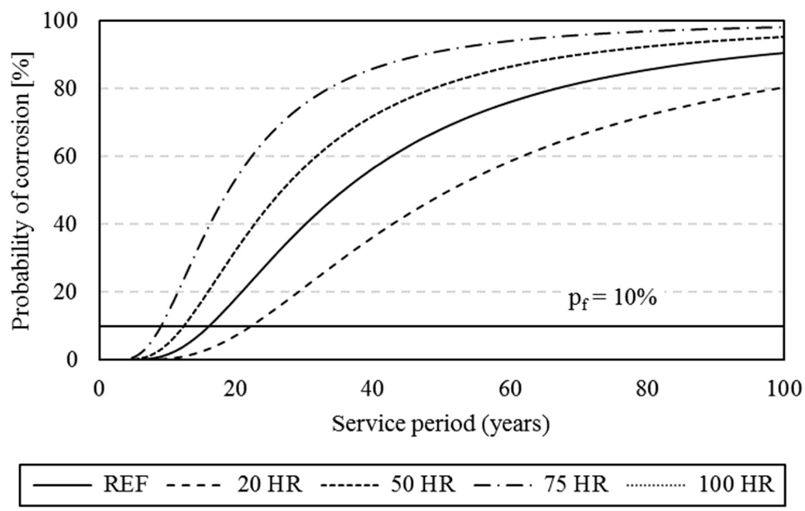

Fig. 3.6. Effect of temperature on the probability of corrosion for $T = 10$ °C.

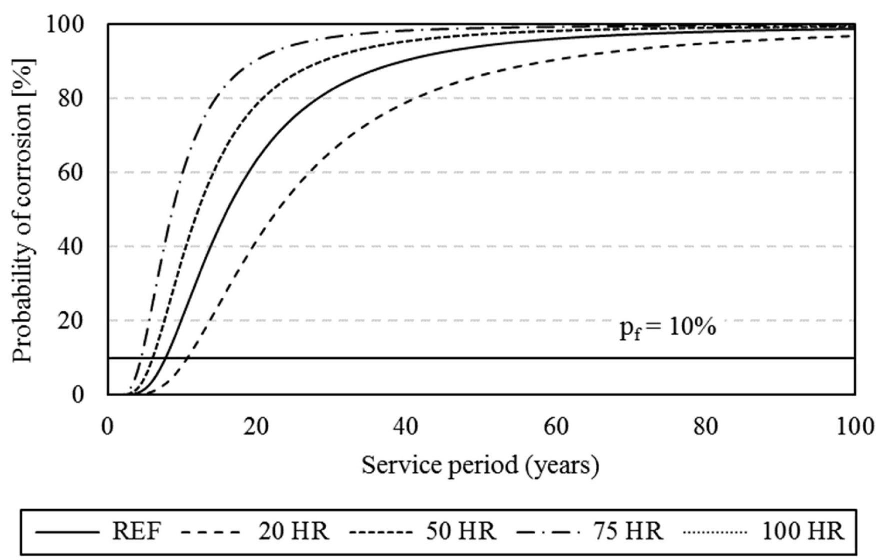

Fig. 3.7. Effect of temperature on the probability of corrosion for $T = 20$ °C.

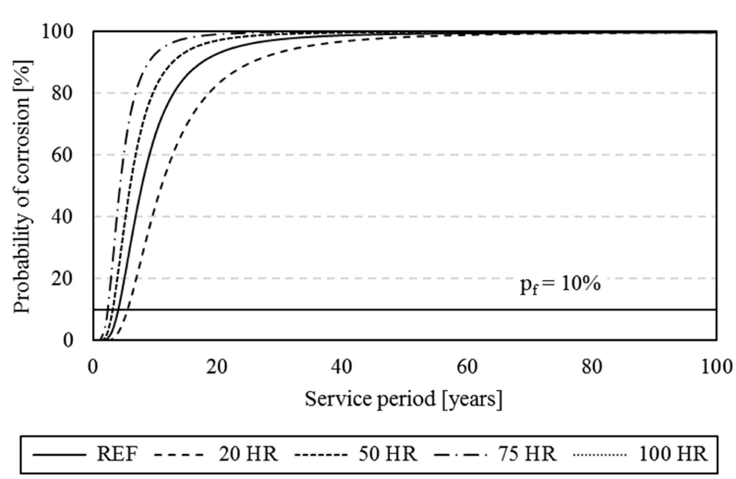

Fig. 3.8. Effect of temperature on the probability of corrosion for $T = 30$ °C.

Furthermore, it is observed that the increase in temperature generated a negative impact on all mixes. The 10°C increase in temperature resulted in reductions in the estimated service life of approximately 50%, which confirms the strong influence of temperature on the diffusivity of chloride ions.

The behavior of the 20 HR mix in the durability analyses may be associated with a slight reduction in the water/binder ratio and better compaction provided by a low level of recycled aggregate substitution, contributing to lower ionic diffusivity. However, this beneficial effect is overcome as the substitution level increases, due to increased porosity and microstructural heterogeneity and consequent decrease in performance.

4. Final considerations

It is important to emphasize that service life estimates resulting from a performance-based approach should not be interpreted as the actual service life of a structure. This type of analysis is subject to uncertainties associated with both the input parameters and the predictive model itself. Still, these results serve as a basis for comparing technical alternatives and selecting the most appropriate solutions, considering the expected performance of the concrete in relation to the environment and the service life required in the design.

The results highlighted the significant influence of concrete cover, temperature, and environmental aggressiveness on the durability of concrete produced with recycled aggregates. It was found that a 10 °C increase in temperature causes reductions of approximately 50%, while a 10 mm increase in the thickness of the cover layer can increase it by about 94%. In addition, an increase of just 2% in the surface concentration of chlorides can cause reductions in the service life in the order of 28 to 56%.

Probabilistic analyses demonstrated that, among the concretes evaluated, the mix with 20% replacement (20 HR) obtained the highest performance. This mix outperformed the reference concrete (REF) in all simulated scenarios.

In contrast, higher replacement levels (50%, 75%, and 100%) showed a reduction in the estimated service life, a behavior attributed to the probable increase in porosity and heterogeneity of the material. The results also showed that increasing the thickness of the cover layer is an effective measure to partially compensate for this loss of performance.

To further enhance the understanding of RCA durability, the following suggestions for future research are proposed: (a) experimental determination of early-age diffusion coefficients and the ageing factor; (b) assessment of chloride ion penetration under natural exposure conditions to establish correlations with accelerated test results; (c) parametric analysis of chloride penetration models; (d) production of concrete mixtures with varying water/cement ratios, cement types, and mineral admixtures (e.g., metakaolin, silica fume) to obtain diffusion coefficients representative of a broader range of mix designs; (e) evaluation of additional durability indicators, such as air permeability; (f) service life estimations considering distinct temperature ranges, cover depths, and environmental aggressiveness levels; and (g) life-cycle cost and cost-benefit analyses of RCA at different replacement levels.

List of Notations

c_{25}	Electrical conductivity obtained at 25°C [mS/cm]
c_T	Electrical conductivity obtained at temperature T [mS/cm]
T	Temperature [°C]
Cl^-	Quantity of chlorides [mol]
V_a	Volume of the anolyte [L]
D_{ns}	Non-steady-state chloride diffusion coefficient [cm^2/s]
e	Thickness of the specimen [cm]
τ	Time lag [s]
φ	Acceleration factor of the electric field [V/cm]
z	Valence of the chloride ion
F	Faraday constant [cal/Veq]
R	Gas constant [cal/mol·K]
T_A	Average temperature of the anolyte during the test [K]
$\Delta\phi$	Normalized electric field [V/cm]
ΔE	Average of the effective voltages measured on both faces of the specimen, during the non-steady-state period [V]
$C_{(x,t)}$	Chloride concentration at depth x_C after a time t (s) [%/mass of cement]
C_S	Chloride concentration on the concrete surface [%/mass of cement]
erf	Gauss error function
x_C	Distance from the edge of the member where the critical chloride concentration C_{cr} occurs [mm]
$D(t)$	Chloride diffusion coefficient in the concrete [m^2/s]
t	Time [s]
D_0	Diffusion coefficient determined at the reference time [m^2/s]
α	Concrete aging factor
t'	Age of the concrete when exposed to ions [years]

k_e Parameter that introduces the influence of temperature on the diffusion process
E_A Activation energy of chloride diffusion [kJ/mol]
$g(x,t)$ Limit state function
C_{cr} Critical chloride concentration [%/mass of cement]
p_f Failure probability of the structure [%]

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Conflict of interest

The authors declared that they have no potential conflicts of interest regarding the research, authorship, and/or publication of this article.

Author contribution

Pietra: Conception; Design; Data Collection & Processing; Analysis & Interpretation; Literature Review; Writer; Critical Review.

Mauro: Design; Supervision; Resource.

Fábio: Supervison; Resource; Materials; Data Collection & Processing.

María: Supervision; Resource; Materials; Data Collection & Processing.

Rita: Conception; Design; Analysis & Interpretation; Literature Review; Writer; Critical Review.

Gustavo: Conception; Design; Analysis & Interpretation; Literature Review.

Data availability

We declare that the publication includes all graphs and data collected or developed during the study.

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