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Can seawater be used as mixing water for durable and sustainable RC structures?

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ABSTRACT

Nowadays the use of chloride-contaminated raw materials is prohibited for reinforced concrete (RC) structures. Beside possible effects on the early stages of cement hydration and the long-term development of strength, the primary reason is corrosion of black steel reinforcement. In fact, it is well known that chlorides, destroying the passivation film, make steel susceptible to pitting corrosion. Thus, design standards worldwide aim at limiting the use of chloride-contaminated materials. However, the use of chloride-contaminated raw materials for the production of concrete would be advantageous since it would allow saving natural resources, such as fresh water, leading to enhanced environmental sustainability. In the framework of a research project financed by the Infravation Program (Advanced systems, materials and techniques for next generation infrastructure), an experimental study is undertaken aiming at demonstrating the safe utilization of seawater and salt-contaminated aggregates (natural or recycled) for a sustainable concrete production when combined with non-corrosive reinforcement to construct durable and economical concrete infrastructures. This paper focuses on a preliminary evaluation of the possibility of replacing fresh water with seawater when combined with different types of stainless steel reinforcement. Through a performance-based approach, RC elements made with fresh water and seawater, different constituents and stainless steel bars were simulated under exposure to different marine environments to define possible materials combinations able to guarantee a target design service life.

Key words: reinforced concrete, seawater, stainless steel bars, performance-based approach, sustainability.

INTRODUCTION

Presently the use of seawater and salt-contaminated aggregates is prohibited for reinforced concrete (RC) structures. The use of seawater may affect some properties, such as the setting time, the workability, the kinetics of hydration of portland cement and, as a result, the early strength and the long-term development of strength of concrete [1]. However, the use of seawater as mixing water is universally considered to be risky due to its high content of chloride salts which can promote corrosion of conventional reinforcement made of black steel. In fact, it is well known that chlorides above a certain threshold may destroy the passivation film of steel embedded in concrete, making it susceptible to pitting corrosion. For such reason, design standards worldwide aim at preventing both the use of chloride-contaminated materials and the further penetration of chloride during the service life of the structure.

However, the construction industry could greatly benefit from the use of chloride-contaminated raw materials for the production of concrete, since great amounts of natural resources such as fresh water or mined rocks for aggregates could be saved, leading to enhanced environmental

sustainability. Particularly, a proper management and use of fresh water is needed in many parts of the world, to sustain this depleting resource, since the World Meteorological Organization reported water scarcity and water stress conditions in countries by 2025. In fact, the increase in world population has demanded a corresponding increase in the availability of resources for human and industrial consumption and the fresh water use has tripled over the last 50 years. A solution would be to investigate possible alternatives aimed at environmental sustainability, as, for instance, the use of seawater for the production of concrete.

Within the framework of ERA-NET Plus Infravation 2014, an infrastructure innovation program on “Advanced systems, materials and techniques for next generation infrastructure” (<http://www.infravation.net/>), the SEACON project - Sustainable concrete using seawater, salt-contaminated aggregates, and non-corrosive reinforcement (<http://seacon.um-sml.com>) was recently started. This project, that involves six academic and industrial partners, is aimed at demonstrating the safe utilization of seawater and salt-contaminated aggregates (natural or recycled) for a sustainable concrete production when combined with non-corrosive reinforcement to construct durable and economical concrete infrastructures. Integral to the study are two experimental tracks.

Firstly, the performance of concrete made with seawater and salt-contaminated aggregate will be compared with that of concrete made with traditional constituents to assess the role of chloride-contaminated raw materials on the properties of fresh and hardened concrete. Secondly, the suitability of using chloride-contaminated raw materials for sustainable and durable RC structural elements will be demonstrated with: i) a grade of stainless steel bars suitable for the required combination of design service life and environmental exposure; and, ii) non-corrosive composite FRP bars. The final objective of the study is to demonstrate the feasibility of this approach from a technical point of view and evaluate its impact on the sustainability of RC structures based on a life cycle assessment approach.

This paper focuses on a preliminary evaluation of the possibility of replacing fresh water with seawater when combined with different types of stainless steel reinforcement, through a model adapted from the performance-based approach “Model Code for Service Life Design”, published by the International Federation for Structural Concrete (*fib*) [2]. RC elements made with fresh water and seawater, different constituents and stainless steel bars were simulated under exposure to different marine environments (in a splash zone) to define possible materials combinations able to guarantee a target design service life of 100 years.

DURABILITY DESIGN APPROACH

Two different marine environments were considered: a temperate climate (e.g., the coast of Mediterranean Sea) and a subtropical climate (e.g., the coast of Florida). Several design options in terms of types of concrete and reinforcement were considered. As far as the type of concrete is concerned, a portland cement (OPC) and a cement with 30% fly ash (FA) were considered with a water/binder (w/b) ratio of 0.45 (maximum value of water/cement suggested by Eurocode 2 [3] for the splash zone). Different types of reinforcing bars were considered: conventional black steel and stainless steels of grades UNS S30453 (low-carbon austenitic stainless steel with 18% Cr, 8-10% Ni), UNS S32304 (duplex stainless steel with 23% Cr, 4% Ni, 0.1-0.6% Mo), UNS S32205 (duplex stainless steel with composition: 22% Cr, 5% Ni, 3% Mo) and UNS S24100 (austenitic stainless steel with 18% Cr, 2% Ni, 12% Mn). The service life was modelled following the probabilistic model proposed by *fib* Model Code for Service Life Design and the limit state equation was solved by means of a Monte Carlo simulation method (10^6 simulations performed for each case).

Limit state equations

For a structure exposed to a chloride-bearing environment, the probability of failure, p_f , was evaluated as the probability that the initiation limit state function, g , reaches negative values:

$$p_f = P\{g < 0\} = P\{Cl_{th} - Cl(d_c, t_{SL}) < 0\} \quad (1)$$

where: Cl_{th} is the critical chloride threshold; d_c is the depth of the outermost rebar; t_{SL} is the target service life; $Cl(d_c, t_{SL})$ is the content of chloride in the concrete at a depth d_c and at a time t_{SL} .

The target service life, t_{SL} , which needs to be defined in the design phase, is guaranteed if the probability of failure p_f is equal or lower than a preset target probability, P_0 , which should be defined in the design phase. According to the *fib* Model Code, the initiation limit state function, g , was evaluated as:

$$g = Cl_{th} - \left\{ C_0 + (C_{s,\Delta x} - C_0) \cdot \left[1 - \operatorname{erf} \frac{d_c - \Delta x}{2 \cdot \sqrt{D_{app,0} \cdot t}} \right] \right\} \quad (2)$$

where: C_0 is the initial chloride content of the concrete; Δx is the depth of the convection zone where, beside diffusion process, other mechanisms of chloride penetration can occur; $C_{s,\Delta x}$ is the substitute chloride surface content, C_s , at the depth Δx ; $D_{app,0}$ is the apparent coefficient of chloride diffusion through concrete.

The apparent coefficient of chloride diffusion of concrete is determined as:

$$D_{app,0} = k_e \cdot D_{RCM} \cdot k_t \cdot A(t) \quad (3)$$

where: k_e is an environmental transfer variable and is a function of the temperature of the element (T_{real}), D_{RCM} is the chloride migration coefficient, k_t is a transfer parameter and $A(t)$ is the sub-function considering the 'ageing'.

Since all the functions and parameters considered in the model cannot be reported in this paper, reference to the *fib* Model Code is made for a detailed description [2].

Selection of values for the design parameters

Although some parameters of the limit state equations are directly given by the *fib* model, other parameters (i.e., D_{RCM} , $C_{s,\Delta x}$, C_0 , T_{real} , Cl_{th}) should be selected at the design stage depending on the specific materials used, the design details and the environmental exposure conditions.

Table 1
Values of input parameters and types of probability density function distribution, PDF, (BetaD = beta distribution; ND = normal distribution; D = deterministic) used for design of an RC element exposed to a marine splash zone

Parameter	Unit	Description	PDF	Option	Mean value	Standard deviation	
Cl_{th}	% by mass of binder	critical chloride threshold	BetaD	black steel	0.6	0.15	
			$0.2 \leq Cl_{th} \leq 2$				
			BetaD	S30453	5	1.25	
			$2 \leq Cl_{th} \leq 8$		stainless steel		
			BetaD	S32205	8	2	
			$3 \leq Cl_{th} \leq 13$		stainless steel		
$C_{s,\Delta x}$	% by mass of binder	chloride content at a depth Δx	BetaD	S32304	4.5	1	
			$2 \leq Cl_{th} \leq 7.5$		stainless steel		
			BetaD	S24100	3.4	0.6	
$2.3 \leq Cl_{th} \leq 5.5$		stainless steel					
C_0	% by mass of binder	initial chloride content	ND	fresh water	0	-	
				seawater-Temperate	1	0.2	
				seawater-Subtropical	0.98	0.2	
d_c	mm	concrete cover	ND	-	to be determined	10	
T_{real}	K	temperature of the structural element	ND	Temperate	293	10	
				Subtropical	298	10	
D_{RCM}	10^{-12} m ² /s	chloride migration coefficient	ND	OPC	6.5	1.3	
				FA	4.5	0.9	
t_{SL}	years	target service life	D	-	100	-	

Table 1 summarizes the input parameters of this study, including their description, the selected values as well as the type of probability density function distribution.

As far as the migration coefficient of chloride, D_{RCM} , is concerned, the *fib* Model Code suggests measuring it directly from the concrete mix through an accelerated test (i.e., the rapid chloride migration test according to the NT-Build 492 [4]). Accordingly, experimental data on D_{RCM} published in a previous work were considered: D_{RCM} of $6.5 \cdot 10^{-12}$ and $4.5 \cdot 10^{-12}$ m²/s ($10.08 \cdot 10^{-8}$ and $6.98 \cdot 10^{-8}$ in²/s) for OPC and FA concretes were assumed, respectively [5]. At this stage, any possible effect on the diffusion coefficient due to the use of seawater as mixing water was neglected (these values will be revised on the basis of the results of ongoing experimental programme). For the substitute chloride surface content, $C_{s,\Delta x}$, a normal distribution, determined in a previous work through literature survey, with an average value of 5% and a standard deviation of 2% of chloride by mass of binder was considered [4]. The average annual temperature of the structural elements, T_{real} , was assumed respectively equal to 20°C and 25°C for the RC element exposed in temperate and subtropical climates. The initial chloride content, C_0 , was considered zero for concretes made with fresh water as mixing water; for concretes made with seawater, mean values of 1% and 0.98% by mass of binder were taken into account, evaluated from the salinity of the Mediterranean Sea and the Atlantic Ocean, respectively, and the selected mix proportions.

Finally, for the critical chloride threshold, C_{th} , the *fib* Model proposes values only for carbon steel, without taking into account corrosion resistant steels and without considering that this parameter depends on the temperature of the environment [6]. Thus, the values of C_{th} for the stainless steel reinforcement were determined through literature data. For S30453 and S32205 stainless steels, values determined in a previous work were taken into account; in particular mean values and standard deviations respectively equal to 5 and 1.25% by mass of binder for S30453 and 8 and 2% by mass of binder for S32205 were considered [7]. As far as S32304 duplex stainless steel is concerned, a pioneer study showed that concrete with mixed-in chloride up to 3% by mass of portland cement did not experience corrosion initiation during 18 months of exposure to an urban environment [8]. The corrosion resistance of S32304 stainless steel was similar to that of S30453 when tests in solution were performed [6,9], whilst a lower corrosion threshold for the S32304 in comparison to S30453 was determined through tests in concrete [6,10]. Hence, for the S32304, a mean value and a standard deviation, slightly lower than those of S30453, of 4.5% and 1% by mass of binder were taken into account. Few data are reported in the literature for the S24100 stainless steel and mean value and standard deviation respectively equal to 3.4% and 0.6% by mass of cement were taken into account as suggested in [11]. Regarding the dependence of C_{th} on the temperature, an approach different from that used for the penetration of chlorides was considered [12]. Chloride diffusion rate is expected to vary as a function of temperature and it is not constant through the year; usually, an average annual value is considered (T_{real}). Conversely, initiation of corrosion may be promoted also by a temporary increase in temperature; hence, it is more significant to consider the maximum values reached in the warmest periods of the year. The two considered environments are characterized not only by different average annual temperatures, but also by different average values of the maximum yearly temperatures; in fact, a variation of 2-4°C between the average value of the maximum yearly temperature in the temperate and subtropical climates could be accounted for. Hence, as a first approximation, the effect of temperature in the subtropical climate was taken into account through a corrective coefficient, k_T , set equal to 0.8 (based on unpublished data).

MODELLING

In order to evaluate the different scenarios, in terms of materials and exposure environments, the probability of failure, p_f , defined as the probability of initiation of corrosion at the end of the design service life of 100 years, was estimated. Figures 1 and 2 show p_f as a function of the mean value of the concrete cover thickness for the two different exposure environments, the two types of concrete made with fresh water and seawater and the five different types of reinforcement considered in this work. As expected, p_f increased when concrete contains seawater for any concrete cover thickness.

To investigate the possibility of using seawater as mixing water in the different exposure conditions, a maximum value of 10% for the target probability, P_0 , can be considered (dashed lines in Figures 1 and 2), in order to determine the minimum concrete cover thickness which guarantees, for each option, this target probability. Figure 3 compares the mean value of concrete cover thickness required when fresh or seawater is used. Considering the OPC concrete (Figure 3a), it can be observed that black steel bars are unsuitable in both environments, even if fresh water is used, since a concrete cover thickness higher than 150 mm (5.9 in.) would be required. The higher C_{th} of stainless steel bars

allows a reduction in the concrete cover thickness both when fresh water and seawater is used as mixing water. The reduction of the concrete cover depends on the corrosion resistance (i.e., the critical chloride threshold) of any specific grade of stainless steel. Assuming that for both the environments realistic values for the critical chloride threshold were taken into account in the simulations, with fresh water, in the temperate climate the minimum value of the concrete cover decreases from values higher than 150 mm (5.9 in.) for black steel bars to 85 mm (3.3 in.) for the austenitic S24100 steel with manganese, to 65 mm (2.6 in.) for duplex S32304 stainless steel and to 60 mm (2.4 in.) for traditional austenitic S30453 stainless steel. An even lower concrete cover thickness could be used with the duplex S32205 stainless steel. Assuming that mixed-in seawater does not affect the chloride diffusion in the hardened concrete, it can be observed in Figure 3a that its use leads to an increase of 5-20 mm (0.2-0.8 in.) of the needed concrete cover thickness, depending on the steel grade (the highest increase was observed on the stainless steel with the lowest corrosion resistance).

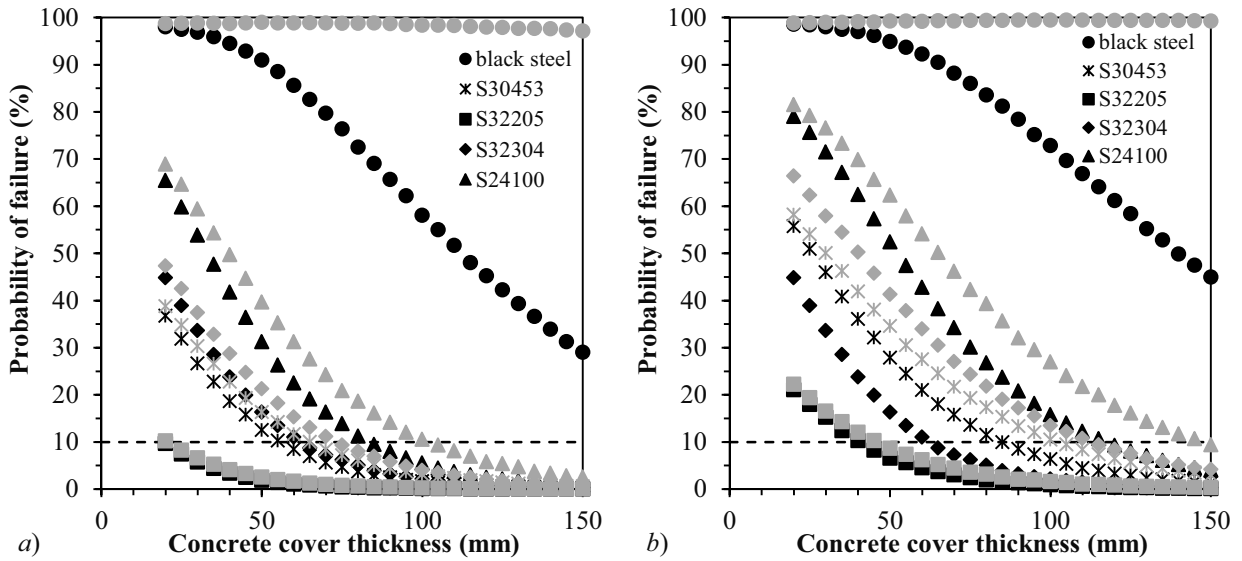


Figure 1: Probability of failure as a function of mean concrete cover thickness, type of reinforcement and initial chloride content (black symbols: fresh water; grey symbols: seawater) for OPC concrete and target service life of 100 years for an RC element exposed to temperate (a) and subtropical (b) climates (100 mm = 3.94 in.).

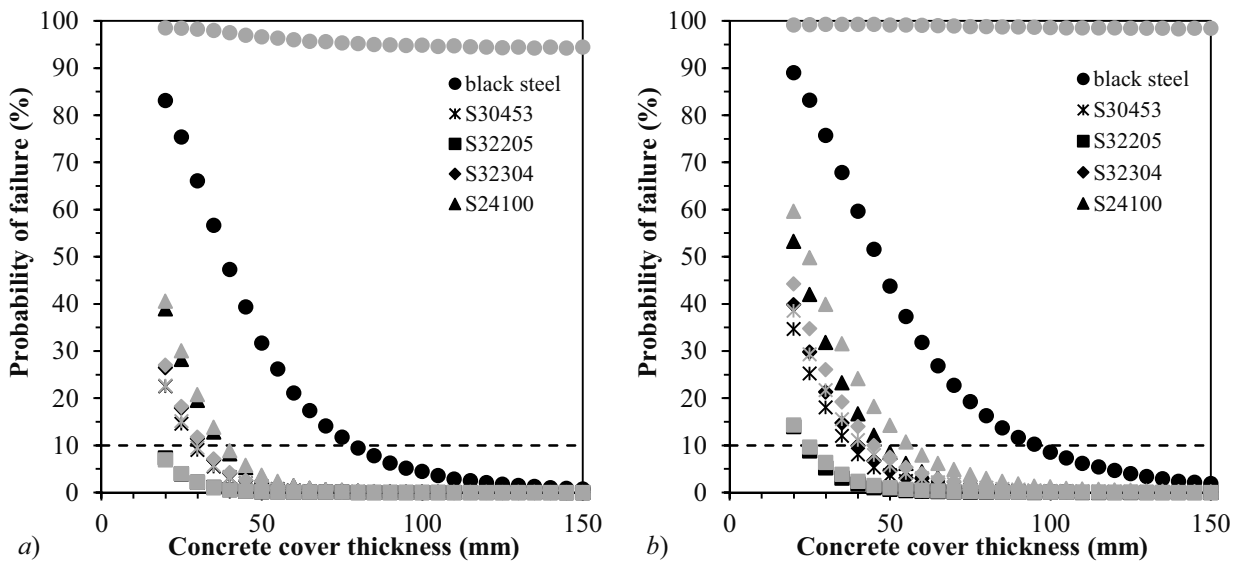


Figure 2: Probability of failure as a function of mean concrete cover thickness, type of reinforcement and initial chloride content (black symbols: fresh water; grey symbols: seawater) for fly ash concrete and target service life of 100 years, for an RC element exposed to temperate (a) and subtropical (b) climates (100 mm = 3.94 in.).

In the subtropical climate, the assumed lower corrosion resistance of each steel grade due to the harsher environment, leads to a further increase of the concrete cover thickness required to guarantee the target service life and the need for impractical concrete cover thickness (higher than 115 mm – 4.5 in.) for the stainless steels with the lower corrosion resistance. Obviously, higher values of the concrete cover thickness are required in case of seawater and, as a consequence, an OPC concrete would require the use of a stainless steel grade with a high corrosion resistance (i.e., the S32205 grade).

The use of FA concrete (Figure 3b), owing to its higher resistance to chloride penetration, allows for each exposure environment and type of stainless steel a reduction of the concrete cover thickness in comparison to that evaluated for the OPC concrete. With fresh water even the black steel requires a lower concrete cover thickness (around 80 and 95 mm - 3.1 and 3.7 in.-, respectively, for temperate and subtropical environments).

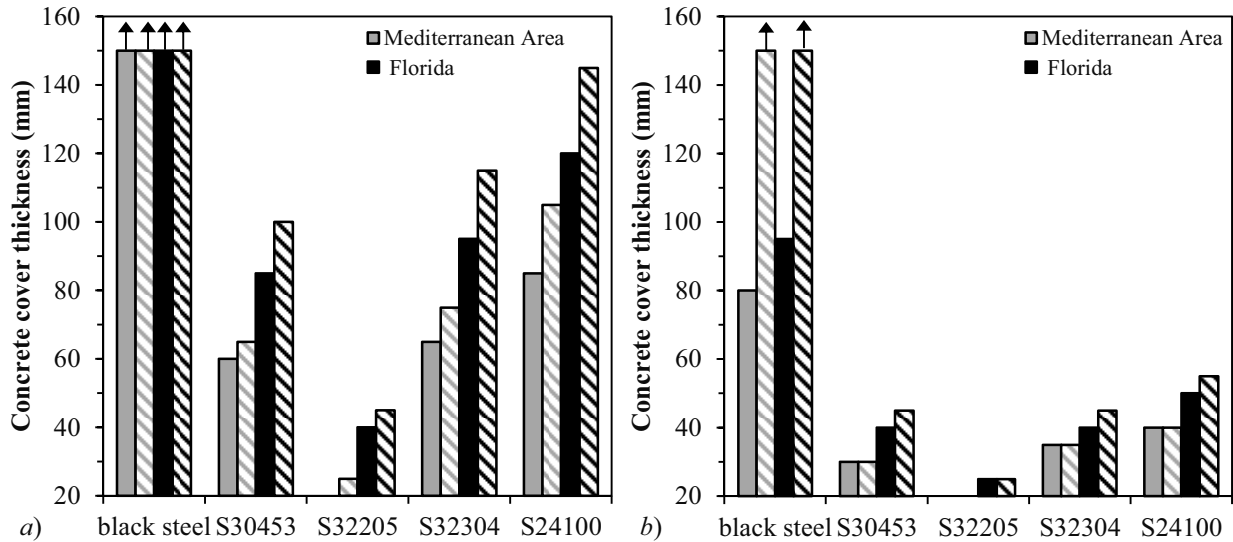


Figure 3: Mean concrete cover thickness needed to guarantee at 10% probability of failure a target service life of 100 years for an RC element exposed to temperate and subtropical climates with concretes made with fresh water (solid background) or seawater (dashed background) as mixing water, OPC (a) or fly ash (b) concrete (100 mm = 3.94 in.).

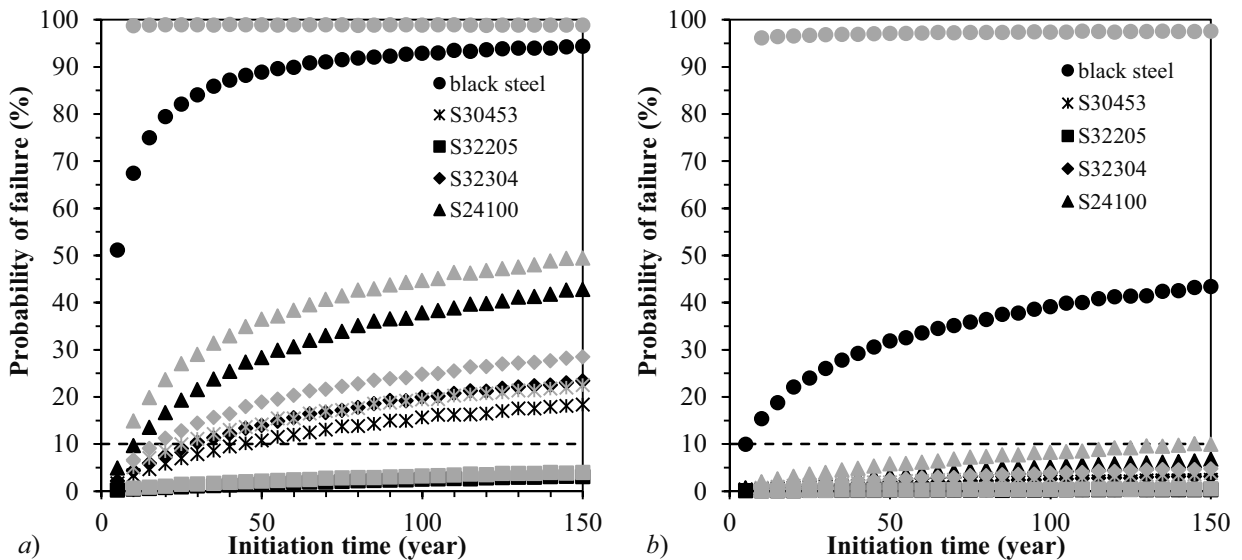


Figure 4: Probability of failure as a function of initiation time, type of reinforcement and initial chloride content (black symbols: $C_0 = 0\%$ by mass of binder; grey symbols: $C_0 = 1\%$ by mass of binder) for OPC (a) and a fly ash (b) concretes and mean concrete cover thickness of 45 mm (1.8 in.) for an RC element exposed to temperate climate.

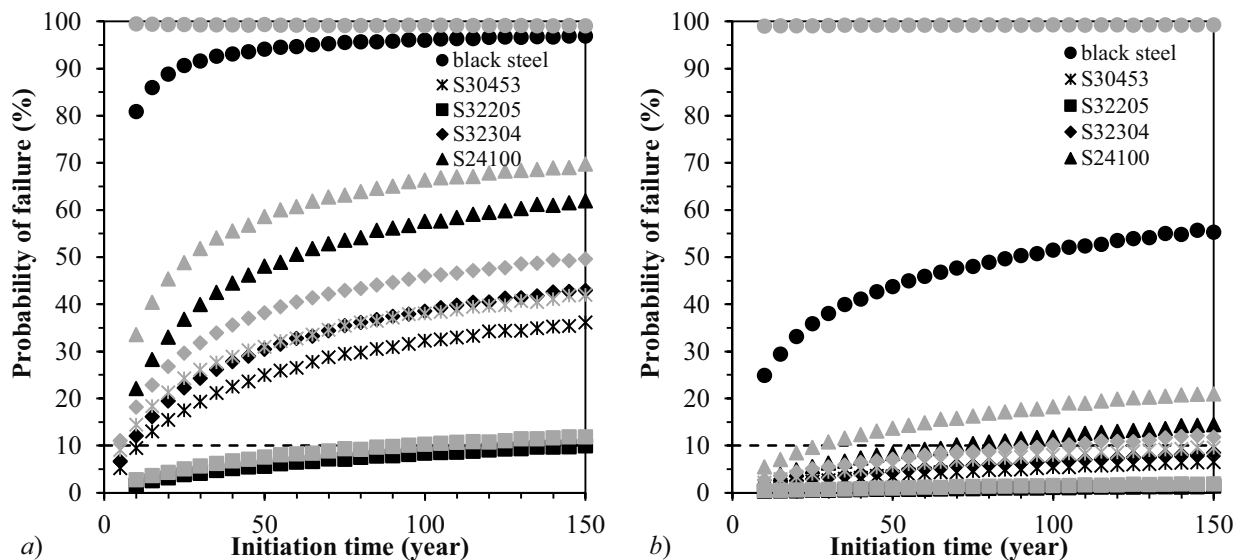


Figure 5: Probability of failure as a function of initiation time, type of reinforcement and initial chloride content (black symbols: $C_0 = 0\%$ by mass of binder; grey symbols: $C_0 = 0.98\%$ by mass of binder) for OPC (a) and a fly ash (b) concretes and mean concrete cover thickness of 45 mm (1.8 in.) for an RC element exposed to subtropical climate.

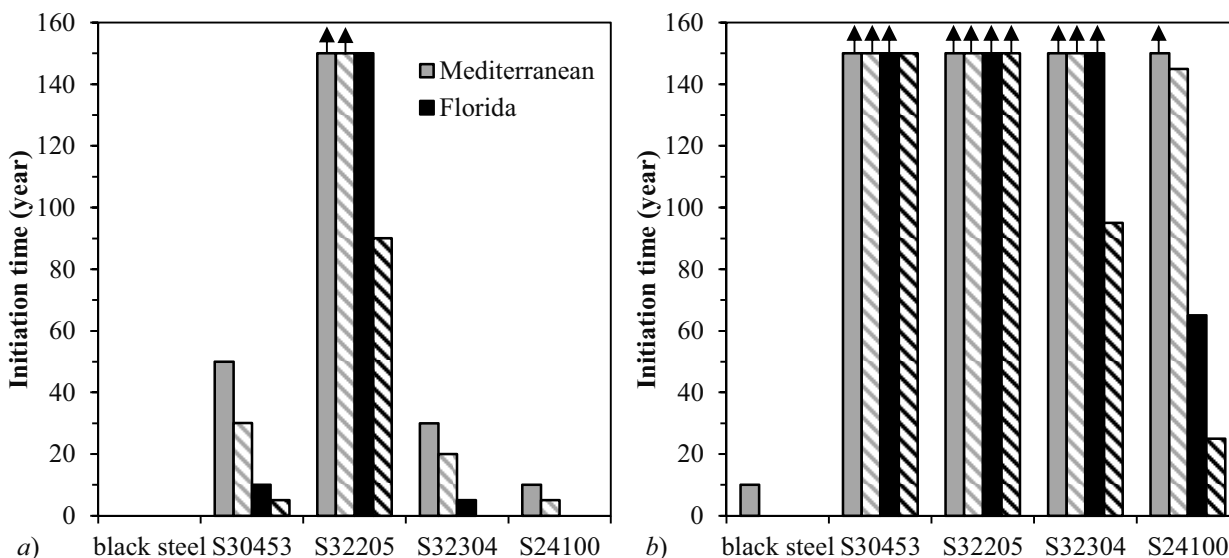


Figure 6: Initiation time guaranteed at a 10% probability of failure and a mean concrete cover thickness of 45 mm (1.8 in.) for an RC element exposed in temperate and subtropical climates with OPC (a) or fly ash (b) concretes made with fresh (solid background) or seawater (dashed background) as mixing water.

In the temperate climate with fresh water, the minimum value of the concrete cover to guarantee a service life of 100 years decreases to: 40 mm (1.6 in.) for S24100; 35 mm (1.4 in.) for S32304; and, 30 mm (1.2 in.) for S30453. Furthermore, for this type of concrete, the use of seawater as mixing water does not lead to any increase in concrete cover thickness, suggesting that the influence of the type of mixing water on the required cover thickness becomes negligible after 100-year service life, due to the major role of chlorides penetrated throughout the service life. However, it should be observed that these results are strongly affected by the significant reduction of the diffusion coefficient in time, due to the ageing factor proposed by the *fib* model for FA concrete (which has been questioned [7]).

The modelling showed that, even with mixed-in seawater, several design options may be selected to reach a service life of 100 years if combined with the use of stainless steel reinforcement, since values of the concrete cover thickness lower than 40 mm (1.6 in.) would be required.

Even in the subtropical environment, although a slight increase of the concrete cover thickness is required, several design options could be available both using fresh water and seawater. Since each type of stainless steel is characterized by a different cost and a different environmental impact for its

production, the most suitable solutions, from cost-effectiveness and sustainability perspectives, could be evaluated by means of LCA and LCC analyses (which will be carried out within the SEACON project).

A different way of analyzing the results of the model would be to estimate p_f as a function of time for a fixed value of concrete cover. In Figures 4 and 5, p_f is shown, for the two different environmental exposure conditions and types of concrete, as a function of the initiation time, assuming a mean concrete cover thickness of 45 mm (1.8 in.), which is a typical value for the splash zone (suggested for instance by Eurocode 2 [3]). From Figures 4 and 5, the service life which can be guaranteed with the target probability of failure of 10% can be calculated for the different options, as shown in Figure 6. With a FA concrete and in the temperate climate, stainless steel bars may guarantee the target probability of failure with a service life even longer than 150 years, even if seawater is used as a mixing water (with S24100 stainless steel a service life of 145 years could be reached). In subtropical climate a long service life (at least of the order of 100 years) could also be reached with S30453, S32304 and S32205 stainless steels, both with fresh water and seawater, whilst with the S24100 stainless steel a lower service life could be guaranteed especially when seawater is employed. The use of an OPC concrete would be suitable to guarantee a reasonable service life in both environment exposure conditions only in combination with the more alloyed (and expensive) S32205 stainless steel.

CONCLUSIONS

In the framework of a multi-partner research project aimed at demonstrating the safe utilization of chloride-contaminated materials when combined with non-corrosive reinforcement, a preliminary assessment of the durability of RC elements in two different marine environments made with mixed-in seawater and different types of stainless steel reinforcement was carried out by means of a probabilistic performance-based approach.

Assuming literature values for the critical chloride threshold of stainless steels and no effect of seawater on the chloride diffusion coefficient, the simulations showed that in both environments several design options (i.e., types of concrete and reinforcement, and concrete cover thickness) may be selected to reach a target service life of 100 years; however in the harsher subtropical environment the available design solutions were more limited. The use of stainless steel reinforcement allowed a significant reduction of the concrete cover thickness in comparison to black steel to values easily obtainable in practice and, for the same grade of stainless steel, higher concrete cover thickness was required in the harsher environment.

The use of seawater as mixing water led to an increase of the required concrete cover thickness in comparison to the use of fresh water, which depended on the type of stainless steel, showing that only some combinations of concrete type and stainless steel grade were suitable. The choice of the most suitable option could be carried out through LCA and LCC analyses. Such analyses as well as validation of the hypothesis made for the input parameters in this work will be carried out in the experimental phase of the SEACON project.

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