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To cite this article: F Lollini *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **296** 012017

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# Seawater and stainless steel bars for sustainable reinforced concrete structures

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**Abstract.** In Mediterranean countries seawater might become a resource for the concrete production for sustainable construction industry. Nowadays its use, since it might induce the corrosion on ordinary carbon steel bars, is prohibited for the realization of reinforced concrete structures. Within the SeaCon Project, the use of seawater as mixing water has been studied in combination with corrosion-resistant reinforcement. This paper, firstly, discusses the influence of chlorides present in the seawater on the concrete properties related to the durability. Afterwards, the corrosion resistance of austenitic (304L and XM-28) and duplex (23-04 and 22-05) stainless steels reinforcing bars, and for comparison of carbon steel, embedded in alkaline and carbonated concretes made with seawater and subjected to different environmental conditions is evaluated. Results showed that seawater accelerated the early strength of concrete, whilst the carbonation penetration, the capillary suction and water absorption were slightly affected. Corrosion tests showed that corrosion did not initiate on 304L, 23-04 and 22-05 stainless steel bars, despite the presence of chlorides since the beginning even in the most aggressive exposure conditions and when concrete was carbonated; XM-28 reinforcement showed a slight change in corrosion behaviour in carbonated concrete exposed to the harshest conditions.

## 1. Introduction

One of the resources of the Mediterranean countries, as well as of other country all over the world is, undoubtedly, seawater, which is the largest water resource on the earth, which accounts for 97% of the available total water. In addition in some areas, freshwater is scarce, making it necessary to seek new water resources and improve the efficiency of their use. Hence, in the last years, attention has been paid to the possible use of seawater as an alternative to freshwater for industrial processes where up to now its use is avoided and construction industry is one of them. As a matter of fact, the construction industry uses several billion tons of freshwater each year to wash the aggregates and mix/cure the concrete, which is the world's most consumed material [1]. In this context, the use of seawater may be potentially attractive and economical for concrete industries, creating sustainable cementitious mixtures with minimal use of freshwater.

Despite the clear potential advantages in terms of sustainability, the use of seawater or other chloride-contaminated materials, is currently forbidden in reinforced concrete by Standards, as indicated, for instance, by EN 206: 2016 which limits the total chloride-ion content in reinforced concrete to 0.2-0.4% by mass of cement [2]. This is mainly due to the associated risks of early corrosion of ordinary carbon steel bars [3] and also to a possible influence on the concrete properties [4].



As far as corrosion risks are concerned, when at the steel bars the chlorides concentration is higher than the critical chloride threshold, the passivity film present on carbon steel rebars in concrete may be locally destroyed, inducing the pitting corrosion. At this regard, the corrosion resistance of carbon steel in concrete made with seawater has been investigated and the majority of the available studies in literature confirmed the unsuitability of seawater [5][6][7] in the concrete production since in this environment the carbon steel reinforcement is highly prone to corrosion. Besides the evaluation of the behavior of the bars in concretes made with seawater, it is needed to consider also its durability-related properties. In general, most of the literature studies evidence the effects of seawater only on the early-properties of concrete. In particular, regarding the role of seawater on concrete workability, a possible reduction on this property could be expected; however some researchers concluded that its effect is minimal [6]. Furthermore, the use of suitable superplasticizer admixtures might be recommended to avoid it.

As far as mechanical performance is concerned, a lot of studies agree that concrete made with seawater increases early-age strength in comparison with ordinary concrete mixed with freshwater [8][9]. However, only few studies are focused on the evolution of mechanical performance over time and on the transport properties of concrete made with seawater; the latter one is of high concern to evaluate the effects of seawater on degradation phenomena [10].

In the SeaCon project “Sustainable concrete using seawater, salt-contaminated aggregates, and non-corrosive reinforcement”, financed by the Infravation program, the combination of stainless steel reinforcement and chloride-contaminated concrete was studied to realize durable and sustainable concrete infrastructures [11][12]. This note reports the results of a part of the research project which has considered austenitic and duplex stainless steels reinforcing bars, and for comparison traditional carbon steel bars, in a reference concrete and in a concrete made with seawater. The corrosion resistance of the different bars in concrete specimens has been studied in several environmental conditions (before and after carbonation), without further chloride penetration. Both concretes have been characterized in terms of mechanical properties, carbonation resistance, capillary suction and water absorption.

## 2. Experimental work

### 2.1. Materials

In this study two concretes were made: the reference mix (Ref) with ingredients without chlorides and the Sea mix (Sea) obtained by replacing freshwater with seawater collected from the Mediterranean sea (Liguria – Italy). The two mixes had a water/cement ratio,  $w/c$ , of 0.52, obtained with 335 kg/m<sup>3</sup> of limestone Portland cement, type CEM II/A-LL 42.5R (in accordance with the European standard EN 197), 175 kg/m<sup>3</sup> of water (freshwater or seawater) and 30 kg/m<sup>3</sup> of carbon fly ash. 1825 kg/m<sup>3</sup> of siliceous aggregate, with three fractions, two sands (0-2 mm and 0-4 mm) and one gravel (4-12.5 mm), was employed for the mixes. For reference concrete and seawater concrete initial chloride contents of 0.02 and 1.1% by cement mass were respectively measured. An acrylic-based superplasticizer was used to reach an *S4* class consistence, which corresponds to a slump of the Abram’s cone between 160 and 210 mm. In Table 1 the composition of the concretes and the results of the slump test are reported.

### 2.2. Mechanical and durability tests

Mechanical properties were tested after various curing times in moist condition (at R.H. > 95% and T = 20°C); in particular, compressive strength and dynamic elastic modulus by means ultrasonic tests were evaluated on two replicate 100 mm cubic specimens after 1, 7, 28, 120 and 360 days of moist curing. To evaluate the durability-related properties of the studied concretes, water absorption at atmospheric pressure, capillary suction and resistance to the penetration of carbonation under accelerated conditions tests were evaluated.

**Table 1.** Composition and properties of the mixes.

	<i>Ref</i>	<i>Sea</i>
cement (kg/m <sup>3</sup> )	335	335
freshwater (kg/m <sup>3</sup> )	175	-
seawater (kg/m <sup>3</sup> )	-	175
fly ash (kg/m <sup>3</sup> )	30	30
0-2 mm sand (kg/m <sup>3</sup> )	490	490
0-4 mm sand (kg/m <sup>3</sup> )	596	596
gravel (kg/m <sup>3</sup> )	739	739
w/c ratio	0.52	0.52
w/b ratio	0.48	0.48
superplasticizer (% mass of binder)	0.71	0.95
slump (mm)	200	185

Capillary suction was performed on 28-day cured cylindrical specimens, with diameter of 100 mm and height of 50 mm. In accordance with EN 13057 standard, after the drying of the specimens, their bottom surfaces were placed in contact with water up to a height of 2 mm and the mass was recorded at different time intervals up to 24 hours. The water absorption per unit surface was then plotted versus the square root of time and the sorptivity coefficient of concrete was evaluated as the slope of the best-fit line. Afterwards, the specimens were submerged until constant mass was reached and the total water absorption (%) was calculated.

The resistance to the penetration of carbonation under accelerated conditions was evaluated on 7-day cured cubic specimens, with 100 mm side, masked with epoxy, to allow the carbonation to penetrate only from two opposite faces, and exposed for 70 days to an environment with 20±2°C, 55±5% R.H. and a constant flux of 4±2% CO<sub>2</sub>. At the end of the exposure, the specimens were split and sprayed with phenolphthalein and the carbonation depth was measured on 20 points of the fracture surface. The accelerated carbonation coefficient  $k_{ACC}$  was evaluated as:

$$k_{ACC} = d/t^{0.5} \quad (1)$$

where  $d$  is the average carbonation depth at time  $t$ .

### 2.3. Corrosion tests

Corrosion tests were performed on 7-day cured concrete specimens, reinforced with ribbed carbon steel rebars and ribbed bars of stainless steel of grades 304L, 22-05 and 23-04, with 18 mm of diameter and ribbed bars of XM-28 with 20 mm of diameter. These stainless steel bars were chosen according to literary review [13]. Their mechanical properties and chemical compositions are shown in Table 2. The stainless steel bars were subjected to commercial sand blasting and pickling, to remove the oxide scale produced during hot forming, whilst carbon steel bars were sand blasted in the laboratory. Before testing, all the reinforcement were degreased with acetone and the two ends of each bar were masked, to expose to the concrete a length equal to 80 mm, in order to avoid crevice corrosion, with a styrene-butadiene-modified cement mortar and coated with a self-amalgamating tape.

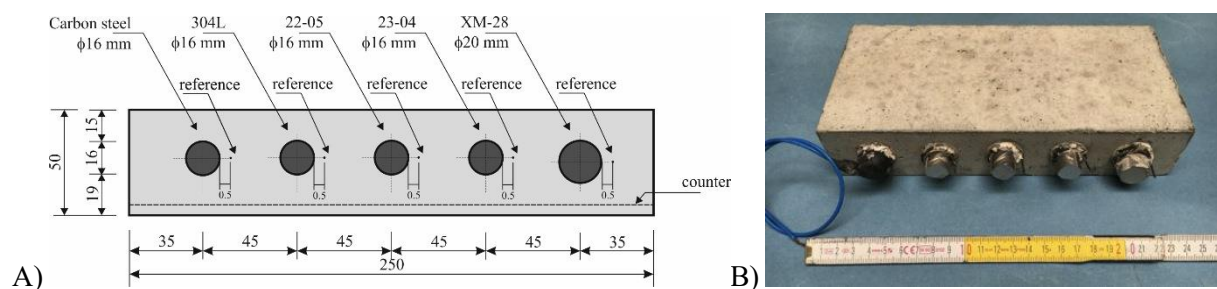
Prismatic specimens, with dimensions of 250×120×50 mm<sup>3</sup>, were made with one bar of each type of steel, with a concrete cover thickness of 15 mm (Figure 1). Three replicate specimens were cast to account for the variability of the results. After the curing, the specimens were exposed in an unsheltered environment, on the roof of the Department of Chemistry, Materials and Chemical Engineering of Politecnico di Milano, without the further penetration of chlorides, to reproduce a structure made with seawater, but exposed far from the sea and the marine aerosol. The three specimens of each mix were exposed outside for a different period: one specimen was exposed for about 4-6 months, another for 7-8 months and the third one for approximately 1 year.

Afterward the corrosion resistance of carbon and stainless steel bars was investigated on two alkaline specimens for each mix exposed to different controlled cycles of temperature and humidity; the third specimen was subjected to accelerated carbonation. Once the entire thickness of the specimens was fully carbonated these specimens were as well exposed to the same controlled cycles of temperature and humidity. In particular, to simulate temperate and tropical environments, the following exposure conditions of temperature (T) and humidity (H) were imposed for 2-4 weeks until stable conditions were reached: T = 20°C/ H = 50% (indoor exposure), T = 20°C/ H = submerged, T = 38°C/ H = 100%, T = 50°C/ H = submerged (only one alkaline specimen was exposed also to T= 50°C/H = 90% and, hence, these results will not be discussed).

During the exposure period, the corrosion behaviour was investigated through electrochemical measurement of half-cell potential of steel ( $E_{\text{corr}}$ ) versus a saturated calomel electrode (SCE), placed on the specimen surface in the central part of each bar, and the linear polarisation resistance measurements ( $R_p$ ). From  $R_p$  measurements, made using the internal references and counter, the corrosion current density,  $i_{\text{corr}}$  was calculated as  $B/(R_p)$ , where  $B$  was assumed equal to 26 mV.

**Table 2.** Mechanical properties (U.S. = ultimate strength; Y.S.<sub>0.2%</sub> = yield strength at 0.2% of deformation;  $A_{gt}$  = total elongation at maximum force) and main alloy elements of the stainless steel bars and carbon steel bars.

Steel name	Mechanical properties			Main alloy elements (%)										
	U.S. (MPa)	Y.S. <sub>0.2%</sub> (MPa)	$A_{gt}$ (%)	C	Cr	Ni	Mo	Mn	N	Cu	Si	S	P	V
304L	760	543	24	0.021	18.51	8.61	0.15	1.31	0.146	-	-	-	-	-
22-05	838	607	24	0.021	22.56	5.26	3.332	1.48	0.158	-	-	-	-	-
23-04	750	524	18	0.019	23.37	4.27	0.30	1.23	0.095	-	-	-	-	-
XM-28	923	672	-	0.11	17.41	2.23	0.18	12.02	0.30	-	-	-	-	-
C	590	540	10.9	0.145	0.10	0.16	0.04	0.87	0.009	0.55	0.14	0.042	0.017	0.001



**Figure 1.** Geometry (A) and photo (B) of reinforced specimen (dimensions in mm).

### 3. Results and discussion

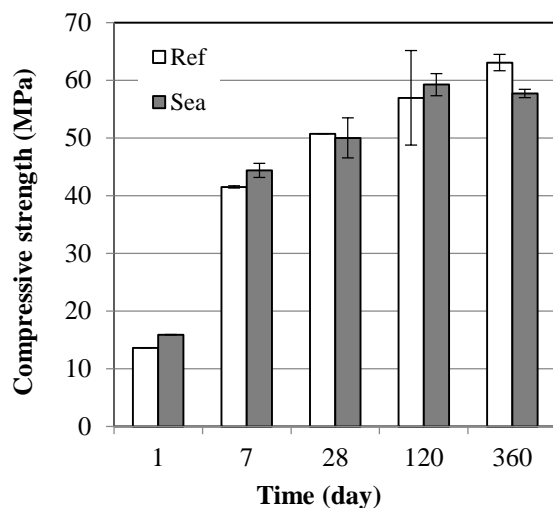
In order to evaluate the suitability of seawater as mixing water for reinforced concrete structures, it is needed to evaluate both the mechanical and durability performances and the corrosion behaviour of the embedded steel bars. In particular, assuming that a sea mix would be employed for structures exposed enough far from the coast that the main expected cause of degradation would be the carbonation-induced corrosion, it is of fundamental importance the assessment of the resistance to carbonation penetration as well as the corrosion behaviour of the bars when the concrete is carbonated.

### 3.1. Mechanical and durability properties

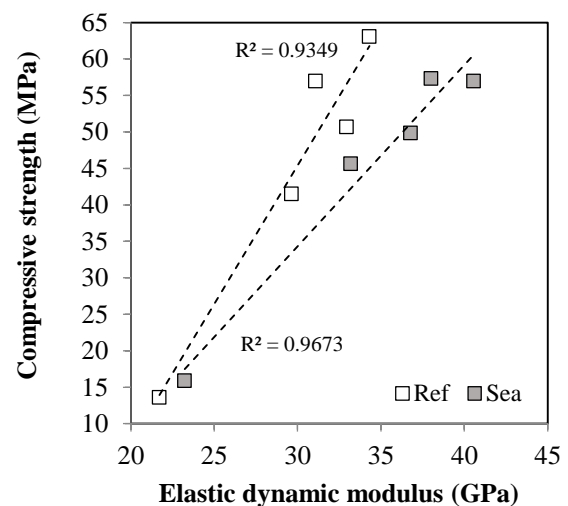
Figure 2 shows the compressive strength measured on the Ref and Sea mixes after different exposure times. As well-known, compressive strength significantly increased within the 28 days, reaching values of about 50 MPa for both types of concrete. In particular, the results showed that seawater accelerated slightly the early strength in comparison to the reference concrete, whilst similar strengths were obtained after longer curing time (360 days seem to be an exception). Mechanical performances of studied concretes were also characterized in terms of elastic dynamic modulus (Figure 3). A correlation between compressive strength and elastic dynamic modulus was found. It can be observed that dynamic elastic modulus of the Ref mix reached values of 33-40 GPa after longer curing time (about 1 year), whilst slightly higher values were evaluated on the Sea concrete.

Beside mechanical strength, for reinforced concrete structures it is of fundamental importance to evaluate if seawater used as mixing water affects the permeability of concrete, which is an important indicator of the concrete durability. As a matter of fact, the rate of the transport of water, carbon dioxide, oxygen and electrical current into concrete has a great influence on the degradation of reinforced concretes. Therefore, the investigation of the ability of concrete to absorb moisture due to capillary suction when it comes into contact with water and its resistance to the penetration of carbonation is of great concern. Table 3 summarizes the results obtained on two replicate specimens for each mix (Ref mix and Sea mix), in terms of water capillary coefficient,  $S$ , total water absorption,  $A$ , and accelerated carbonation coefficient,  $k_{ACC}$ , evaluated after 70 days of exposure under accelerated carbonation through equation (1). To investigate the influence of seawater on a given durability property,  $P$ , Figure 4 shows the ratio between the property evaluated as an average on the Sea mix ( $P_{sea\ mix}$ ) and the same property evaluated as an average on the reference concrete ( $P_{ref\ mix}$ ). In general it can be observed that this ratio is, for every analyzed property, lower than 100% indicating an increase of the resistance to the transport processes in seawater concrete.

In particular, it can be observed that capillary suction coefficient, equal to  $0.89\text{ kg/m}^2\cdot\text{h}^{0.5}$  in the Ref mix decreased to  $0.61\text{ kg/m}^2\cdot\text{h}^{0.5}$  in the Sea concrete, mainly due to an accumulation of salts in the cement matrix of Sea mix and the changes in fluid properties, i.e., surface tension and viscosity, which might influence uptake of water. Similar results were also found in terms of total water absorption.



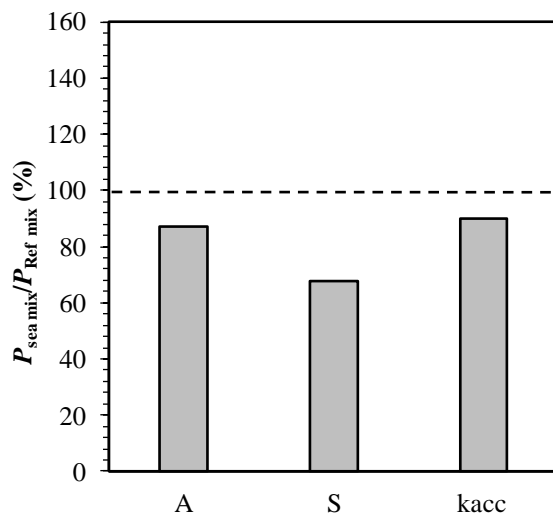
**Figure 2.** Compressive strength of Ref and Sea mixes evaluated on two replicate specimens after different times in moist conditions.



**Figure 3.** Relationship between the compressive strength and the elastic dynamic modulus of Ref and Sea mixes evaluated after different curing time in moist conditions.

**Table 3.** Water capillary coefficient,  $S$ , total water absorption,  $A$ , accelerated carbonation coefficient,  $k_{ACC}$ , evaluated on two replicate specimens for each mix.

	<i>Ref</i>		<i>Sea</i>	
$k_{ACC}$ (mm/year <sup>0.5</sup> )	39.1	40.0	37.7	33.5
$A$ (%)	4.54	4.44	4.13	3.70
$S$ [kg/(m <sup>2</sup> ·h <sup>0.5</sup> )]	0.90	0.88	0.63	0.58

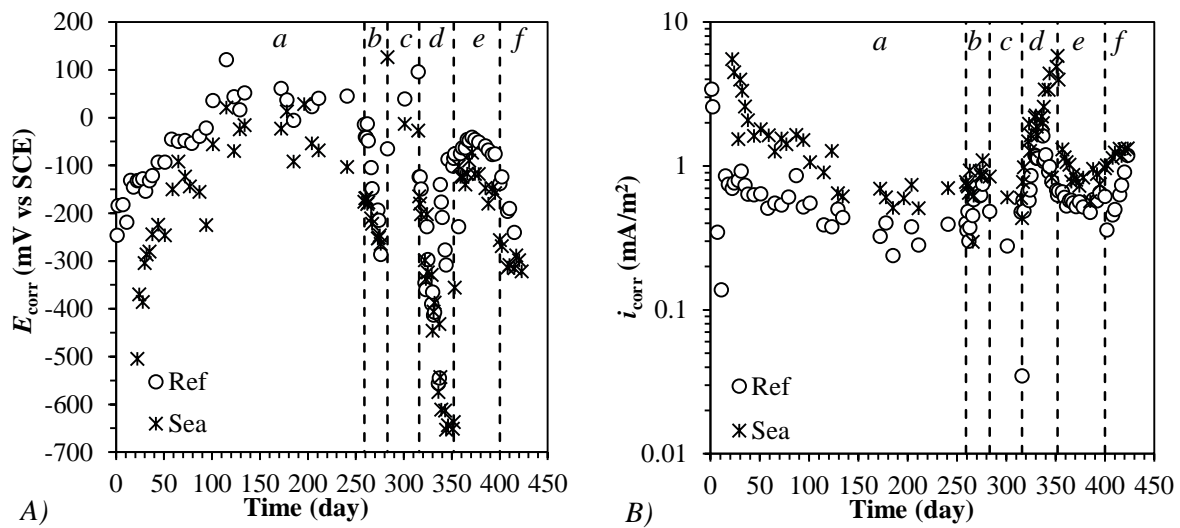
**Figure 4.** Effect of the use of seawater in concrete on its different durability properties,  $P$ , measured as a ratio  $P_{sea\ mix} / P_{Ref\ mix}$  (average value of two replicate specimens): sorptivity,  $S$ , water absorption,  $A$ , accelerated carbonation coefficient on 7-day cured specimens,  $k_{ACC}$ .

In Table 3 it can be observed that the accelerated carbonation coefficients ranged between 33-40 mm/year<sup>0.5</sup> among the different concretes and lower values were measured on the Sea mix (maybe due to the accumulation of salts in the cement matrix and their consequent hygroscopic effect). Hence, it seems that the use of seawater did not affect relevantly the resistance of concrete to carbonation.

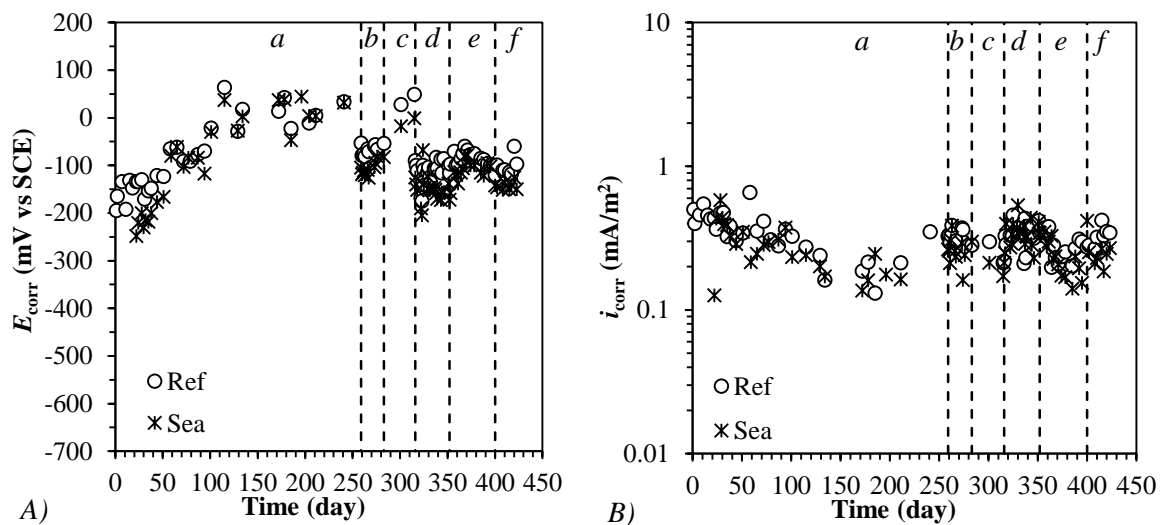
### 3.2. Corrosion behaviour of carbon and stainless steel bars

The corrosion potential ( $E_{corr}$ ) and corrosion current density ( $i_{corr}$ ) of the bars in concrete were measured immediately after casting. As an example, Figures 5 and 6 show the monitoring of the corrosion potential and the corrosion current density respectively for carbon steel and stainless steel of grade 304L in the alkaline Ref and Sea concretes (only results on one specimen are reported). They were exposed initially to an unsheltered environment and then to the cycles of temperature and humidity (results on the other alkaline specimen were similar). The starting date of the exposure was shifted in order to have the same ending point, to compare measurements taken in the same day and to account for possible variations of the corrosion parameters due to variation of exposure conditions.

After casting, the corrosion potential of carbon steel embedded in the Ref concrete was around -250 mV vs. SCE, and after about 28 days it approached values around -120 mV vs. SCE, suggesting the formation of the passivation layer (Figure 5). An initial value of corrosion potential of about -500 mV vs. SCE was detected on the carbon steel bars in the Sea mix, which increased in time, still remaining lower than -200 mV vs. SCE. A further increase of the potential of all the carbon steel bars was observed in the first months of outside exposure, due to the reduction of the humidity of the concretes, followed by stable conditions, even if with some fluctuations due to weather variations.



**Figure 5.** Evolution in time of the corrosion potential (A) and corrosion current density (B) of carbon steel bars embedded in the Ref and Sea concretes exposed to different environmental conditions: unsheltered outdoor environment, a; T = 20°C/ H = submerged, b; T = 20°C/ H = 50%, c; T = 38°C/ H = 100%, d; T = 50°C/ H = 90%, e; T = 50°C/ H = submerged, f.



**Figure 6.** Evolution in time of the corrosion potential (A) and corrosion current density (B) of stainless steel bars of grade 304L embedded in the Ref and Sea concretes exposed to different environmental conditions: unsheltered outdoor environment, a; T = 20°C/ H = submerged, b; T = 20°C/ H = 50%, c; T = 38°C/ H = 100%, d; T = 50°C/ H = 90%, e; T = 50°C/ H = submerged, f.

A comparable trend was observed for the corrosion current densities of the carbon steel bars: in the Ref concrete values of the order of 5 mA/m<sup>2</sup> were measured at the beginning, followed by a decrease (values lower than 1 mA/m<sup>2</sup> were reached); in the Sea mix average corrosion current densities in outside exposure were slightly higher and around 1 mA/m<sup>2</sup> (Figure 5B).

During the cycles of temperature and humidity, it can be noticed in Figure 5 that the potential of the carbon steel embedded in the Sea concrete decreased during the exposure to T = 38°C/ H = 100%, approaching values around -650 mV vs. SCE, whilst the corrosion current density increased significantly, approaching 7 mA/m<sup>2</sup>. This clearly shows that pitting corrosion initiation occurred on carbon steel in wet and hot environment. Corrosion initiation was confirmed also during exposure at

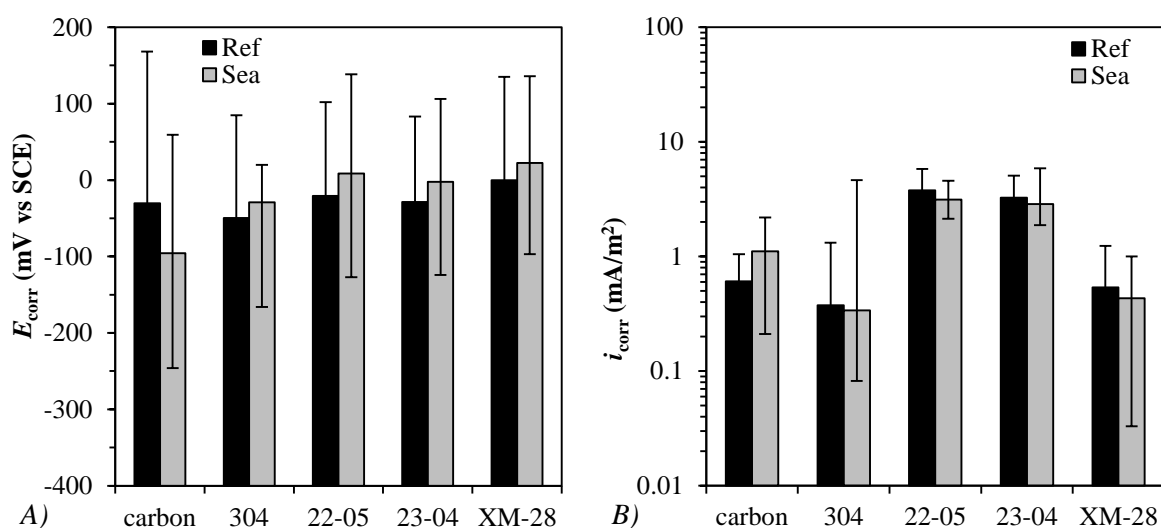


50°C and submerged. As expected, the passivity conditions of the carbon steel bars embedded in Ref concrete were retained also when exposed to the different exposure cycles as confirmed by the insignificant variation of the corrosion potential and corrosion current density.

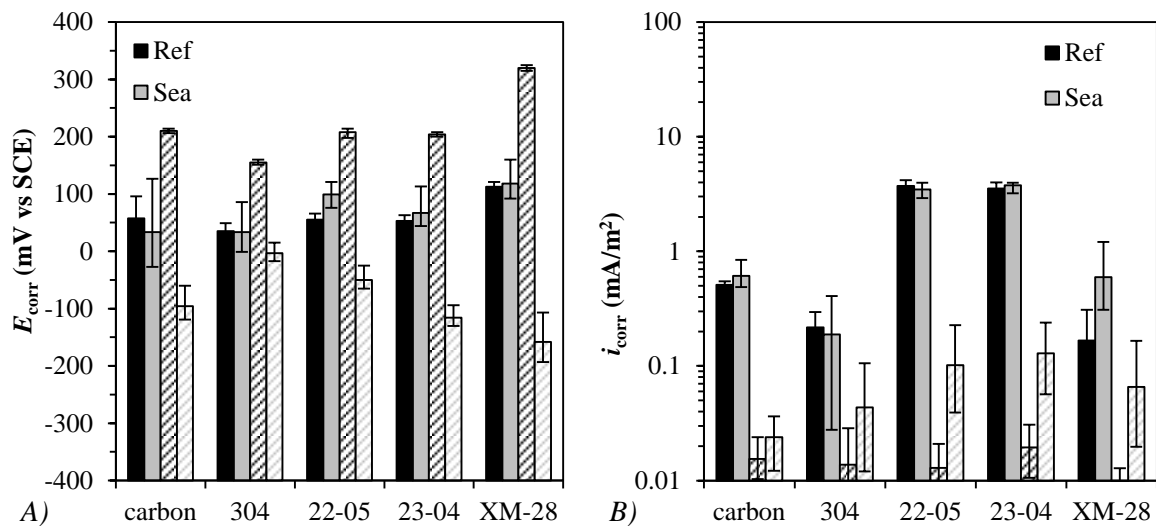
As far as the stainless steel of grade 304L is concerned, in the first 28 days of natural exposure a progressive increase of corrosion potential (Figure 6A) and a decrease of corrosion current density (Figure 6B) was noted in both concretes. In the following months, a further increase of the potential, due to the drying of the specimens, was reached; then only slight fluctuations due to climatic variations were observed. The bars showed a similar corrosion behaviour when embedded in the Ref and Sea concretes. The exposure to 20°C and relative humidity of 50% led to a slight increase of the potential, due to the further drying of the specimens, whilst during the immersion at 20°C and the exposure to 38°C and 50°C, the potential decreased to values lower than those reached at the end of the outside exposure, which however could not be related to the initiation of corrosion, but to a variation of concrete humidity.

Figures 7-11 summarize the average values and the range of variability of corrosion potential and corrosion current density measured on all the bars, i.e. carbon steel and the different grades of stainless steel, embedded in the Ref and Sea concrete mixes, both alkaline and carbonated, and exposed to the different environmental conditions. As a matter of fact, during the service life of a reinforced concrete structure, carbonation can reach the depth of the bars although, according to the results previously showed, after different exposure times in the Ref and Sea mixes. The average values of corrosion potential and corrosion current density were calculated considering all the specimens exposed to the same conditions and neglecting the transient periods. The variability was evaluated considering the maximum and minimum values reached in each exposure condition and obtained from the specimens with the same mix.

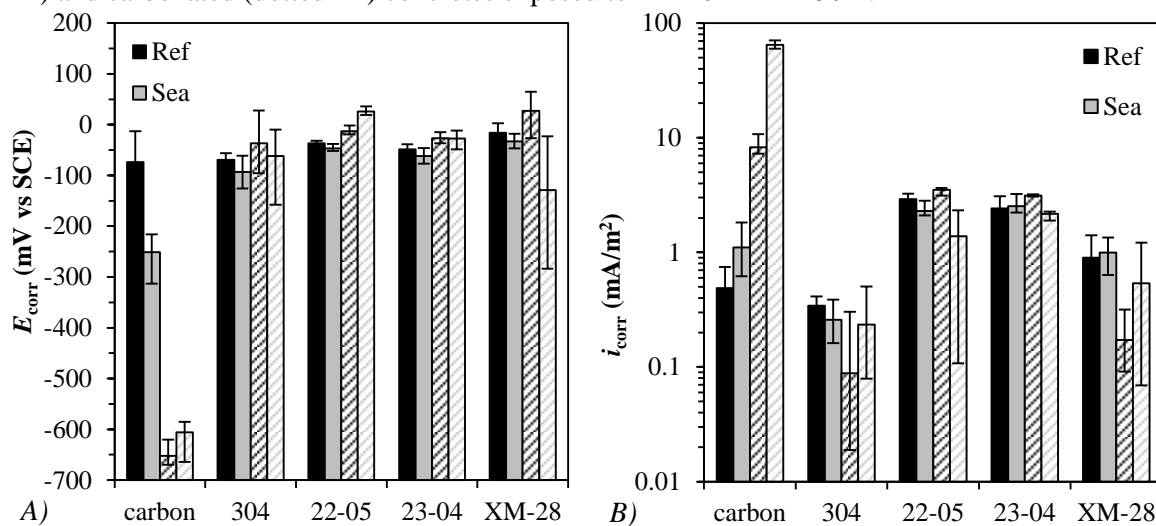
It can be observed that when exposed outside in the mild climate of Milan the carbon steel bars embedded in alkaline concretes, made both with freshwater and seawater, showed corrosion current densities lower than 1-2 mA/m<sup>2</sup>, suggesting that no corrosion initiation occurred on the steel reinforcement. Both the corrosion potential and the corrosion current density of the different grade of stainless steel when embedded in the Ref and Sea mixes and exposed outdoor were comparable, clearly indicating the maintenance of passive conditions (Figure 7).



**Figure 7.** Average values and range of variability of corrosion potential (A) and corrosion current density (B) of carbon steel and stainless steel bars of different grades embedded in alkaline concretes exposed to unsheltered outdoor environment.



**Figure 8.** Average values and range of variability of corrosion potential (A) and corrosion current density (B) of carbon steel and stainless steel bars of different grades embedded in alkaline (full fill) and carbonated (dotted fill) concretes exposed to  $T = 20^{\circ}\text{C}/ H = 50\%$ .



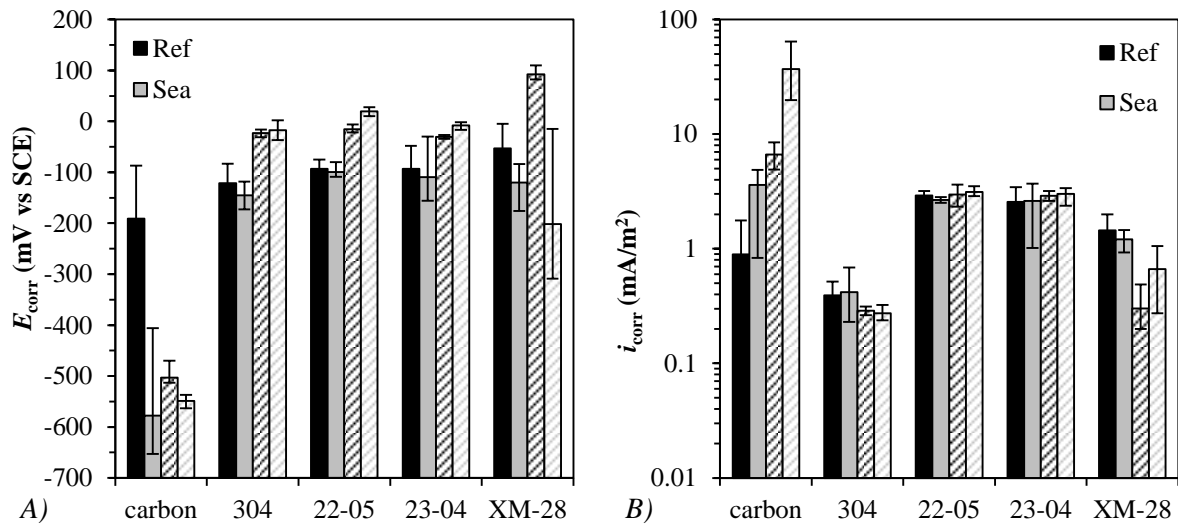
**Figure 9.** Average values and range of variability of corrosion potential (A) and corrosion current density (B) of carbon steel and stainless steel bars of different grades embedded in alkaline (full fill) and carbonated (dotted fill) concretes exposed to  $T = 20^{\circ}\text{C}/ H = \text{submerged}$ .

The corrosion potential of all the bars embedded in the Ref and Sea alkaline concretes slightly increased during the exposure at  $T = 20^{\circ}\text{C}$  and  $H = 50\%$  in comparison to that measured in outdoor conditions, since the concrete was drier, still revealing the maintenance of passive conditions. In the Ref carbonated concrete, also on carbon steel bars no more protected by the passive layer, higher corrosion potential and lower corrosion current density than those measured in the Ref alkaline were detected, since concrete is more resistive (Figure 8).

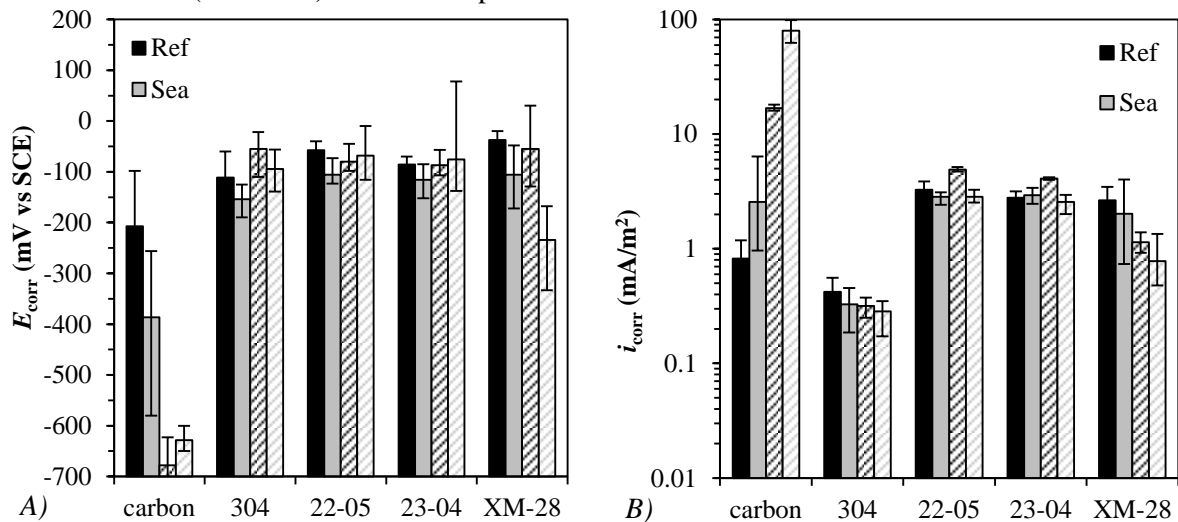
A slight decrease of the corrosion potential of the carbon steel bars embedded both in Ref and Sea alkaline concretes immersed in water can be observed in comparison to that measured outdoor, however corrosion current density was still lower than  $1\text{--}2\text{ mA/m}^2$ , suggesting that corrosion did not initiate (Figure 9). Conversely, in carbonated concrete,  $E_{corr}$  of carbon steel bars experienced a significant drop, reaching values around  $-600\text{ mV vs. SCE}$ , clearly indicating that, in carbonated concrete, corrosion propagated. In the Ref concrete, a corrosion current density higher than  $10\text{ mA/m}^2$  was measured, whilst in concretes made with seawater, values even higher than  $70\text{ mA/m}^2$ , were evaluated, indicating that the

presence of chlorides led to a significant increase of the corrosion rate (Figure 9). In this exposure condition none of the stainless steel bars embedded in the Sea concretes showed any sign of initiation of corrosion, indicating their suitability also when the concrete is carbonated (Figure 9).

During the exposure cycles at temperatures of 38°C and 50°C a decrease of the corrosion potential and an increase of the corrosion current density were observed in the carbon steel bars embedded in the Ref and Sea alkaline concretes in comparison to those observed at 20°C (Figures 10 and 11). Corrosion potential around -200 mV vs. SCE and corrosion current density lower than 1 mA/m<sup>2</sup> were evaluated on the bars embedded in Ref concrete, whilst significant changes were noted for carbon steel bars embedded in concrete made with seawater.



**Figure 10.** Average values and range of variability of corrosion potential (A) and corrosion current density (B) of carbon steel and stainless steel bars of different grades embedded in alkaline (full fill) and carbonated (dotted fill) concretes exposed to  $T = 38^{\circ}\text{C}/ H = 100\%$ .



**Figure 11.** Average values and range of variability of corrosion potential (A) and corrosion current density (B) of carbon steel and stainless steel bars of different grades embedded in alkaline (full fill) and carbonated (dotted fill) concretes exposed to  $T = 50^{\circ}\text{C}/ H = \text{immersed}$ .

As a matter of fact, corrosion potential dropped to values lower than -400 mV vs. SCE and corrosion current density increase to values higher than 2.5 mA/m<sup>2</sup>, clearly indicating the initiation of corrosion due to the higher environmental aggressiveness. The corrosion potential of the carbon steel bars further

dropped when bars were embedded in the carbonated concretes. Regarding the stainless steel exposed to these aggressive conditions, a decrease of the corrosion potential of all the bars can be observed, even those embedded in alkaline concretes made with seawater, even if values higher than -200 mV vs. SCE were measured. No significant differences of corrosion current densities were observed on these bars embedded in both types of concrete, suggesting that even harsh environmental conditions did not lead to the initiation of corrosion. The corrosion behaviour of stainless steel of grades 304L, 22-05 and 23-04 embedded in the carbonated concretes was similar to those in the alkaline concretes, indicating that these bars did not experience the initiation of corrosion with chloride contents present in the cement matrix due to the use of seawater, also when carbonation reached the reinforcement. Conversely, the corrosion behaviour of the stainless steel of grade XM-28 in Sea concrete, according to the measurement of corrosion potential, seemed to change after carbonation and when exposed at 50°C; however corrosion current density did not clearly confirm that corrosion initiation occurred. A more prolonged exposure in the harshest environment might lead to a clear initiation of corrosion. Hence, the grades 304L, 22-05 and 23-04 showed to be suitable to be used in combination with Sea concrete in all the exposure conditions, even those that simulated the harshest exposure conditions. As a matter of fact, also when concrete is carbonated, the initiation of corrosion did not occur. The stainless steel XM-28, which has a lower corrosion resistance in comparison to the others, due to its chemical composition (due to the presence of manganese), showed to be suitable in combination with alkaline Sea concrete, whilst after carbonation its corrosion behaviour in the harshest conditions was slightly different in comparison to that observed in the reference concrete without chlorides, suggesting a possible initiation of corrosion. Hence, its suitability in the most aggressive environments when the concrete is carbonated needs to be further assessed.

#### 4. Conclusions

Seawater was employed as mixing water to cast both plain concretes and reinforced concretes with carbon steel bars and stainless steel bars of different grades. On plain concrete the effect of seawater on mechanical and durability-related properties was studied. It was observed that seawater accelerated the early strength of concrete cured in moist conditions, however the strength after longer curing slightly decreased in comparison to the mix made with freshwater. The use of seawater slightly decreased the water permeability of concrete and slightly increased the resistance of concrete to carbonation due to the accumulation of salts in the cement paste.

On reinforced concrete specimens, corrosion tests were carried out to evaluate the suitability of different stainless steel bars to be employed in Sea concrete, both alkaline and carbonated, when exposed to controlled cycles of temperature and humidity, without further chloride penetration. Seawater can be used for the production of concrete in combination with stainless steel bars of grades 304L, 22-05 and 23-04, also when carbonation is expected to reach the bars depth, since these types of stainless steel bars maintained the passivity even when exposed to the harshest environmental conditions (tropical environment). Stainless steel of grade XM-28 was suitable in alkaline Sea concrete, whilst it showed a possible initiation of corrosion after carbonation in environments with the highest temperature and humidity. Carbon steel bars corroded in alkaline concrete made with seawater and exposed to tropical environment.

#### Acknowledgments

The project was made possible with the financial support received from the Infravation Program under Grant Agreement No. 31109806.005-SEACON. The opinions in this paper are those of the authors and not necessarily those of the sponsors or collaborators. The Authors are grateful to the partners who provided the materials (Buzzi Unicem and Valbruna).

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