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ORIGINAL ARTICLE

The service life of reinforced concrete structures in an extremely aggressive coastal city. Influence of concrete quality

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Abstract Corrosivity category of the atmosphere in coastal regions is usually very high. Reinforced structures frequently show short service life if adequate measures are not applied. Determination of time-to-corrosion-initiation (t_i) and time to corrosion with induced cracking (t_{cc}) to calculate the service life in buildings located in coastal cities is not usually performed. Changes in t_i and t_{cc}, depending on the *w/c* ratio, and concrete covering thickness, were determined in extremely aggressive coastal outdoor exposure site located within 10 m of the shoreline in Havana, one of the most aggressive coastal sites in the world. The electrochemical corrosion rate was determined in the reinforced concrete specimens. It is a very important parameter to follow environmental degradation of concrete. Environmental parameters were determined at the site. Calculated Chloride deposition rate is over the maximum level established in ISO 9223 standard (S3). Effective capillary porosity, compressive strength and ultrasonic pulse velocity were determined for all specimens. An acceptable service life was obtained for *w/c* ratio 0.4. However, effective capillary porosity is an important parameter to determine the concrete quality assessment before building reinforced structures exposed to extreme corrosivity. It is recommended to consider this parameter to predict a service life in very aggressive coastal sites.

Keywords Coastal city · Service life · Atmospheric corrosion · Effective capillary porosity · Environment

1 Introduction

Many reinforced concrete (RC) structures located in coastal cities and exposed to the direct influence of marine aerosols present generally a severe deterioration, indicative of short service life (S_l), caused mainly by atmospheric corrosion of the reinforcement steel [1–4]. The RC structures are often built using very permeable concretes with low quality.

Different softwares (*Life-365, Eucon, and Duracon/fib MC SLD*) have already been developed to

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calculate the S_l of RC structures in coastal cities [5]. Some input basic parameters as cement type, concrete constituents, water/cement (*w/c*) ratio, additions, air content, concrete covering thicknesses, and protective systems, play a fundamental role in the determination of S_l. However, some input basic parameters depending on concrete quality as effective capillarity porosity, compressive strength, ultrasonic pulse velocity, and behavior of electrochemical corrosion rate in the reinforcement steel are not included in the software. Atmospheric transitory processes such as chloride deposition rate, relative humidity, and wind speed influencing in the corrosivity category of the atmosphere, and in the electrochemical corrosion rate in the reinforcement steel, neither are included in the software as input basic parameters [6, 7].

In Tuutti´s model, when the level of damage increases due to the behavior of atmospheric corrosion of reinforcement steel in the time of exposure, different times are defined (Fig. 1). The calculate of S_l in the RC structures should consider only the sum of the time-to-corrosion-initiation (t_i) plus time to corrosion with induced cracking (t_{cc}). Indeed, the rapid appearance of t_i and t_{cc} depends on the concrete quality. Moreover, induced cracking of the concrete cover thicknesses caused by atmospheric corrosion of the reinforcement steel defines the end of S_l in the RC structures. Hence, t_i and t_{cc} should be obtained as other results in the softwares to calculate the S_l in the RC structures in coastal cities based on the atmospheric corrosion of the reinforcement steel.

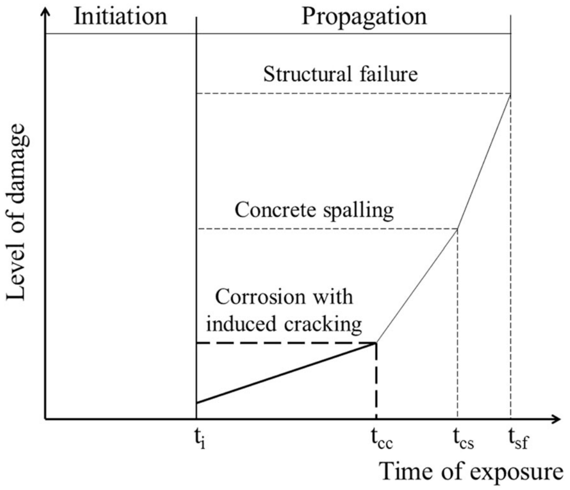

Fig. 1 Tuuti's model. Different times defined as function of atmospheric corrosion of reinforcement steel

To calculate the S_l in the RC structures located in coastal cities, only one study was found, based in the t_i and t_{cc} obtained from the determination and prediction of atmospheric corrosion of the reinforcement steel. RC specimens prepared in the laboratory were exposed in a coastal outdoor exposure site [8].

A comparative study for measuring the electrochemical corrosion rate of reinforcement steel was carried out in RC specimens exposed to marine environments [9]. Three different techniques (galvanostatic pulse, electrical resistivity, and half-cell potential) were used. The electrochemical corrosion rate of reinforcement steel in the splash zone was higher than in the tidal zone. A clear relationship between t_i at the tidal zone and the splash zone was not observed. The t_i decreased when the *w/c* ratio increased from 0.35 to 0.5. However, the authors stated that, the procedure was not very accurate for the determination of t_i; so that the S_l of the RC structures in the marine environment was not calculated.

In the last century, an international research project (DURACON) with the participation of 11 Ibero-American countries, was executed to study the effect of coastal tropical climate on RC structures for more than one year. The RC specimens were prepared using the existing materials in each country [10]. A typical description of atmospheric environments in the 11 coastal outdoor exposure sites placed in coastal cities was carried out. Two types of RC specimens prepared in the laboratory (*w/c* = 0.45, 0.65, and concrete cover thicknesses 10, 20, and 30 mm) were exposed at each site. The compressive strength, elastic modulus, chloride ions permeability, and effective capillary porosity were measured for concrete quality characterization. According to results shown, time to initiate depassivation, considered as t_i, was determined only in the RC specimens of *w/c* ratio 0.65 in two countries (Portugal and Venezuela) and calculated from the behavior of the electrochemical corrosion rate of reinforcement steel at the time of exposure. In this way, t_{cc} could also have been obtained, and determine the S_l of RC structures exposed to the coastal climate.

The city of Havana is located at the western side of the Cuban Isle (2°58', 23°10 NL and 82°30', 82°06' WL). Many RC structures built at a short distance from the sea present a severe deterioration with a short S_l, caused by atmospheric corrosion of the reinforcement steel [11, 12]. The main objective of this study is to demonstrate the expected S_l of RC structures built, and those intended to be built, in a coastal city like Havana. RC specimens (*w/c* ratios 0.4, 0.5, 0.6, and concrete cover thicknesses 20 and 40 mm) were prepared. RC specimens were exposed for three years in a coastal outdoor exposure site, located at 10 m of distance from the sea on the shoreline in the coastal city of Havana. To estimate the corrosivity category of the atmosphere in the coastal outdoor exposure site, typical description of atmospheric environments was carried out.

To confirm the results, visual observation of RC specimens exposed during the three years of study in the coastal outdoor exposure site, was used. The results obtained in this research were included in the development of Cuban Standards for RC structures located in Cuban Coasts [13].

2 Experimental program

2.1 Materials used in the RC specimens prepared

Ordinary Portland cement P-350 was used. Calcareous sand with a modulus of fineness of 3.62 and hard limestone gravel with nominal size 19 mm were used as fine, and coarse aggregates.

The chemical compositions of the cement, gravel and sand are presented (Table 1).

2.2 Concrete mixtures proportions

Three concrete mixtures proportions with different *w/c* ratios (0.4, 0.5, and 0.6) were used in the preparation of the specimens (Table 2). The concrete mixtures proportions used were chosen to minimize the percentage of voids between the fine and coarse aggregates. A superplasticizer admixture, to obtain concrete mixtures with fluid consistency and to assure good compaction, was used. Corresponding fits for each dose of materials were used to ensure a 1 m^3 net volume of concrete. When the concrete mixtures were designed, aggregates were weighed until constant weight. Each dose was different when the *w/c* ratio changed.

2.3 Specimens elaboration

Six RC specimens, two for each *w/c* ratio (0.4, 0.5 and 0.6) in straight rectangular prism form, dimensions 200 × 200 × 200 mm, were prepared (Fig. 2) [14]. Carbon steel molds were used. In order to achieve the concrete cover thicknesses of 20 and 40 mm, two reinforcement steel bars were placed inside each RC specimen. Three RC specimens, one for each *w/c* ratio were exposed in a coastal outdoor exposure site during three years of study: 2008-first year, 2009-s year, and 2010-third year. The other three RC specimens were taken as a reference and remained in the laboratory.

The reinforcement steel bars used (12.5 mm diameter (ø) and 200 mm length (L)) were submitted to chemical cleaning before immersion in fresh concrete mixtures deposited in the steel molds. Previously, a solution composed of 500 ml of concentrated hydrochloric acid ($\rho = 1.19\ \mathrm{g\ ml^{-1}}$) and 3.5 g of hexamethylenetetramine in distilled water, up to 1000 ml, was used to eliminate the poor corrosion products existing on the surface of the reinforcement steel. Twenty-four reinforcement steel bars, four for each RC specimen, were first cleaned with a cloth and placed in a stove at the temperature of 50 °C for 45 min. Afterward, the bars were stored in desiccators [15]. The reinforcement steel bars were immersed in the concrete mixture up to a length of 160 mm. The other 40 mm length of the bars remained outside of the RC specimens to be connected with the electrochemical instruments. The exterior parts of the reinforcement steel bars were covered with adhesive tape. It‘s a temporary atmospheric corrosion protection when RC

Table 1 Chemical composition of the materials

Components (%)	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	L.O.I
Cement	20.64	4.83	3.27	63.64	1.26	1.94	0.56	0.45	3.41
Gravel	7.86	0.58	1.02	45.15	3.96	0.15	0.01	0.34	40.93
Sand	1.42	0.68	0.30	45.46	3.52	–	0.07	0.05	48.50

Table 2 Concrete mixture proportion used in the experiment

w/c	Cement (kg m^{-3})	Water (kg m^{-3})	Superplasticiser (kg m^{-3})	Slump (mm)
0.4	365	148	1.7	150
0.5	365	186	1.5	170
0.6	365	222	1.0	180

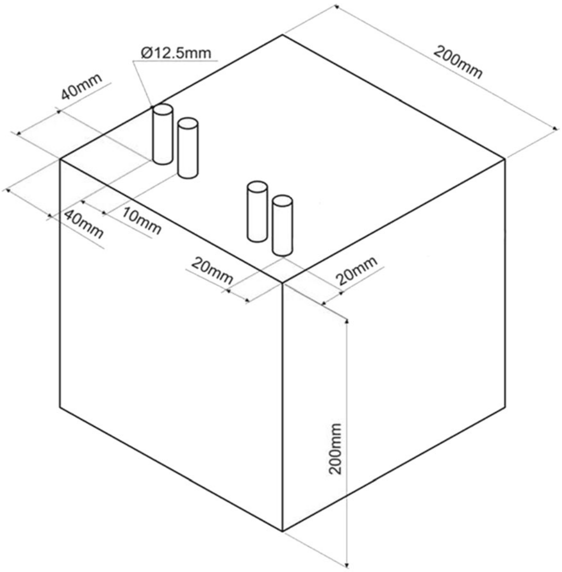

Fig. 2 Diagram of RC specimen prepared

specimens were exposed at the coastal outdoor exposure site.

Six concrete specimens, two for each *w/c* ratio 0.4, 0.5, and 0.6, with the same form and dimensions, but without reinforcement steel bars, were also prepared.

Another twenty-four concrete specimens in cylindrical form (300 mm height × 150 mm diameter), eight for each *w/c* ratio (0.4, 0.5, and 0.6) were prepared in carbon steel molds.

The compaction processes in RC and concrete specimens for the removal of entrapped air in the concrete mixture were carried out using a vibrating table on each cubic and cylindrical carbon steel molds. All molds were moistened before the concrete mixtures were poured.

The concrete mixtures remained in the molds for 24 h. Following this, all RC and concrete specimens were submitted to a water immersion curing process for 28 days. The average water temperature was 23 °C [16].

2.4 Coastal outdoor exposure site

A coastal outdoor exposure site located at 10 m distance from the sea was selected in the coastal city of Havana. It was placed in front of the sea, without the shielding effect caused by structures or vegetation. The height above sea level was 11 m and the geographical coordinates were: 2°58′23°12 NL and 82°42. 82°06 WL.

The aggressivity agent's deposition was determined during the first year. Two dry plate devices and two cellulose filter plate devices were placed in a wooden rack. The chloride deposition rate $(Cl^{-}DR\text{-}mg\ m^{-2}d^{-1})$ was determined from the dry plate device which was composed of absorbent cloth (dimensions 320 mm × 220 mm). The sulfur compound's deposition rate $(SO_x^{-}DR\text{-}mg\ m^{-2}d^{-1})$ was determined using the cellulose filter plate device which was composed of a porous filter paper with an alkaline surface and dimensions of 150 mm × 100 mm. To ensure the impact of the marine aerosol on the surface, the four devices (positioned at an angle of 45° concerning the horizontal) were oriented toward the predominant wind direction. The devices were located at 3 m height above the ground, under a shed with a gabled roof, and protected from the rain [17].

2.5 Atmospheric environment

Two values of aggressivity agent's deposition as $Cl^{-}DR$, and $SOx^{-}DR$, as well as, the monthly average of meteorological parameters were determined and monitored monthly during the first year (from October 2007 up to September 2008)[22]. Meteorological parameters as Relative humidity (*RH*-%), air temperature (*T*°-C) and wind speed (*WS* -m s^{-1}) data were obtained from the Meteorological Centre of Havana located relatively close to the coastal outdoor exposure site.

2.6 Corrosivity category in the coastal outdoor exposure site

Annual average $Cl^{-}DR$ data was recalculated using the Wet Candle method *(* S_{wc}*),* starting from the annual average $Cl^{-}DR$ determined by the dry plate method *(* S_{wc}*)* using the relation established in the ISO standard [22]:

$$S_{wc} = 2.4S_{dp} \tag{1}$$

Annual average $Cl^{-}DR$, $SOx^{-}DR$, RH, and T were used to calculate the atmospheric corrosion rate (µm y^{-1}) of carbon steel and zinc using dose–response functions established in the ISO standard [22]. The values of atmospheric corrosion rate were used to estimate the corrosivity category of the atmosphere in the coastal outdoor exposure site.

2.7 Concrete quality

Criteria for the concrete quality assessment, depending on compressive strength, ultrasonic pulse velocity and effective capillary porosity, are established in the DURAR net corresponding to CyTED program [18].

2.7.1 *Compressive strength*

Values (eight) of compressive strength *(*f_{ck}*-MPa)* for the three *w/c* ratios in the concrete specimens in cylindrical form were obtained [19]. Test machine of maximum axial compression force 2000 kN mm^{-2} was used.

2.7.2 *Ultrasonic pulse velocity*

Values (eight) of ultrasonic pulse velocity (*UPV-m* s^{-1}) in the three concrete specimens (straight rectangular prisms form) without reinforcement steel, for each *w/c* ratio, were determined. The direct transmission method was used. Four values between each opposite side were obtained [20]. A small thickness of grease (petrolatum) was applied to enable a good coupling and electric wave transmission between the transducers. A Tico Proceq Testing Instrument mark, US-made, measurement range 15 µs to 6550 µs (10-6 s) and bandwidth 54 Hz was used. Before starting measurements, a calibration using the concrete reference bars was made.

2.7.3 *Determination of effective capillary porosity*

Three concrete cylindrical cores were extracted from the other concrete specimens in straight rectangular prism form without reinforcement steel. The three cylindrical concrete cores were cut by tungsten saw. Eight concrete cylindrical specimens (62 mm diameter and 20 mm thickness) were obtained for each *w/c* ratio. Values (eight) of effective capillary porosity (ε_e-%) were determined for each *w/c* ratio. The Göran Fagerlund methodology based on capillary water absorption determination was used [21].

2.8 Electrochemical corrosion rate(I_c) in the reinforcement steel bars

The electrochemical corrosion rate *(*I_c *-µA* cm^{-2}*)* was considered as an indicator of the atmospheric corrosion in the reinforcement steel bars. Four I_c values for each reinforcement steel bar were measured at two concrete cover thicknesses (20 mm and 40 mm) each year before extraction of dust samples in the three RC specimens exposed in the coastal outdoor exposure site.

The I_c in the reference specimens (stored in the laboratory) was measured only in the first year (2008-first year). In this way, the eight measurements obtained, four in each reinforcement steel bar, were plotted versus time of exposure (2008-first year, 2009-s year, and 2010-third year). The data was also plotted versus concrete cover thickness and the *w/c* ratio increase.

A GECOR-8TM corrosimeter was used for measuring the I_c. To improve the electric conductivity of the measurement system, dampened cloth was placed between the surfaces of the RC specimen and the instrument's sensor. The sensor was placed on the surfaces of the RC specimens by pressing it by hand (Fig. 3).

The polarised surface area introduced to the instrument was 65.25 cm^2. The potential range was ± 20 mV with a sweep speed of 12 mV s^{-1}. The instrument allows the determination of the I_c according to the Stern Geary equation:

$$I_c = \frac{B}{A * Rp} \tag{2}$$

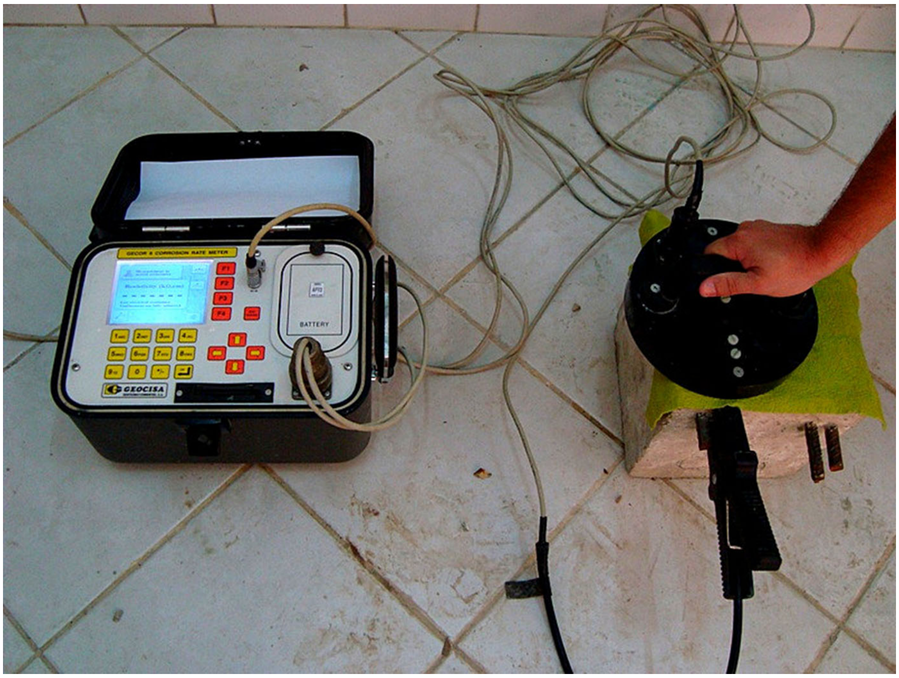

Fig. 3 Measurements of $I_c$in reinforcement steel in the RC specimens using corrosimeter

where B is a constant (26 mV), A is the polarised surface area (critical area) of the reinforcement steel bar, and Rp is the polarization resistance. Criteria established about the I_c magnitude for the S_l of RC structures can be found in the DURAR net of the CyTED program [18].

2.9 Statistical models

For the prediction of the atmospheric corrosion of reinforcement steel bar in RC specimens at a *w/c* ratio 0.4 and concrete cover thickness of 20 mm from 3 to 20 years, data were adjusted to an increasing linear power regression:

$$I_c = at^b \tag{3}$$

t = Time of exposure (data may be from 3 to 20 years).I_c = electrochemical corrosion rate, considered an indicator of atmospheric corrosion of reinforcement steel.a and b = constants.

For the prediction of atmospheric corrosion of reinforcement steel bar in RC specimens with a *w/c* ratio of 0.4 and concrete cover thickness of 40 mm, a Statistical model of Cumulative Sum was used. The initial and average values of I_c was 0.04 µA cm^{-2}. For each initial value of I_c, the average value is subtracted. The cumulative sum was determined from zero, by adding the difference between the initial and average values of the electrochemical corrosion rate.

3 Results

3.1 Typical description of atmospheric environment

A high monthly aggressivity agent's deposition rate ($Cl^{-}DR$, and $SO_x^{-}DR$) is observed during the winter months (October–April) (Fig. 4a, b). The monthly average of *WS* reached the highest values at the same period of the year (Fig. 4b).

Although the monthly aggressivity agent's deposition rate was lower during the summer months (May–September), the monthly average can also be considered elevated. Chloride and sulfate ions salts come from the sea. They are transported in marine aerosol. However, due to strong industrial activity (Oil refinery) located at the northeast of the coastal outdoor exposure site, sulfate ion salts and some sulfur compounds are dragged by the predominantly northeast winds during all the year in the coastal city of

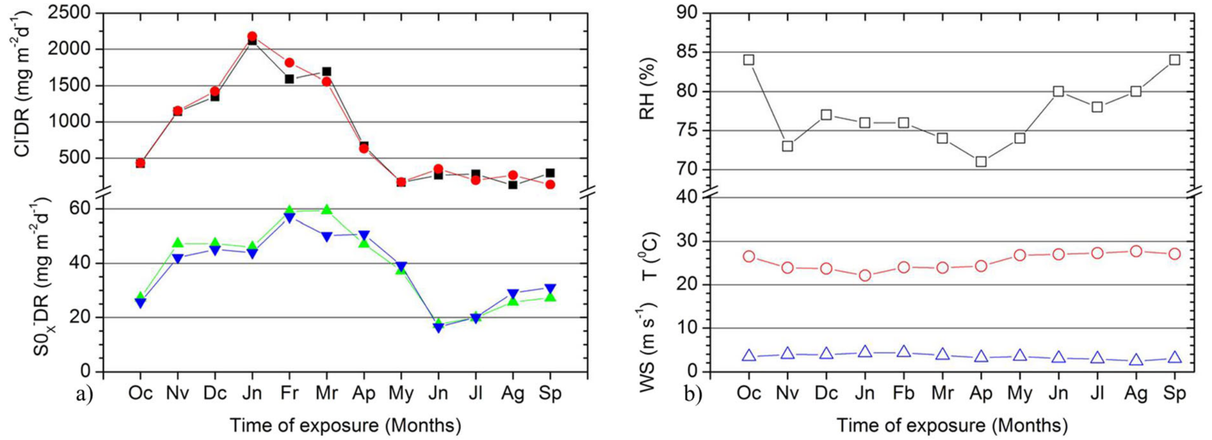

Fig. 4 Behavior of monthly Cl^-DR, and SO_x^-DR (**a**). Monthly average of RH, T, and WS (**b**), in the COES during the first year of the study

Havana. A slight SO_x^-DR increase during the summer period is due to the non-occurrence of penetrating cold fronts (June to September) (Fig. 4a).

The annual average Cl^-DR and SO_x^-DR were 850 mg m^{-2}d^{-1} and 38 mg m^{-2}d^{-1}, respectively. According to ISO 9223 standard, the atmosphere can be classified as coastal-industrial. Also, the annual average Cl^-DR recalculated using the Wet Candle method (S_{wc}), was 2040 mg m^{-2}d^{-1}. Therefore, many RC structures are exposed to one of the most aggressive atmospheres (coastal-industrial) showing a short S_l with a severe deterioration, caused by atmospheric corrosion of the reinforcement steel.

On the other hand, the annual average RH, T, and WS was 77%, 25.3 °C, and 3.4 m s^{-1}, respectively. The levels of these meteorological parameters offer favorable conditions for fast atmospheric corrosion of the reinforcement steel bars in many RC structures in the coastal city of Havana. The high annual average RH and Cl^-DR cause chloride deposition to occur in saline dissolution form on RC structures [22].

3.2 Corrosivity category of the atmosphere

The values of atmospheric corrosion rates (μm y^{-1}) for carbon steel, and zinc were calculated introducing data corresponding to annual averages of Cl^-DR and SO_x^-DR, RH, and T, in dose–response functions established in ISO standard [17].

According to values of atmospheric corrosion rates, carbon steel, and zinc were exposed to an extreme (CX) corrosivity category of the atmosphere. This information is also very useful for galvanized steel. Carbon and galvanized steels are metallic materials commonly used as reinforcements in RC structures. Therefore, RC structures, built at a short distance from the sea are exposed to extreme (CX) corrosivity in the coast of Havana City (Table 3).

Many RC structures show a severe deterioration, caused by atmospheric corrosion of the reinforcement steel bars. Hence, to meet the requirements for durability, depending mainly on concrete quality, as well as, of the atmospheric transitory processes influencing the corrosivity category of the atmosphere such as Cl^-DR, SO_x^-DR, RH, T, and WS, as well as in the I_c in the reinforcement steel bars, it is a very important aspect to calculate the S_l in RC structures exposed in coastal cities, before proceeding with building work. On the other hand, corrosivity categories of the atmosphere, and high levels of aggressive agents in a coastal zone, can be directly used for technical and economic analyses, and for a rational choice of protection measures of the RC structures.

3.3 Basic parameters of concrete

The measurements of the basic parameters of concrete in the specimens after 28 days of curing, depending on the w/c ratio are presented (Table 4). The determined standard deviation (SD) and coefficient of variation (CV) are very low. In this way, the values (eight) for the average f_{ck}, UPV, and ε_e, are very useful information concerning the concrete quality. The average f_{ck} is

Table 3 Corrosivity categories of the atmosphere estimated in the coastal exposure site

Corrosion rate (μm y^{-1})/Corrosivity category (C)			
Carbon Steel	C	Zinc	C
425.40	CX $200 > r_{corr} > 700$	22.55	CX $8.4 > r_{corr} > 25$

Table 4 Parameters determined in concrete specimens at different *w/c* ratios

w/c	ε_e (%)	f_{ck} (MPa)	UPV (m s^{-1})	w/c	ε_e (%)	f_{ck} (MPa)	UPV (m s^{-1})	w/c	ε_e (%)	f_{ck} (MPa)	UPV (m s^{-1})
0.4	7.0	37	4 160	0.5	11.6	30	4 109	0.6	19.7	25	3 900
	7.7	37	4 280		12.8	30	4 110		19.9	26	3 910
	7.4	36	4 200		12.3	30	4 170		19.5	26	3 910
	7.2	36	4 290		14.9	30	4 100		21.3	26	3 930
	6.3	35	4 270		15.7	30	4 050		20.6	26	3 930
	6.7	36	4 270		13.5	31	4 070		18.3	26	3 960
	7.6	36	4 240		14.9	30	4 090		18.2	26	3 980
	6.6	36	4 260		14.0	29	4 150		20.2	26	3 970
Av	*7.06*	*36*	*4 246*	*Av*	*13.7*	*30*	*4 106*	*Av*	*19.7*	*26*	*3 936*
S.D	*0.50*	*0.64*	*44.70*	*S.D*	*1.42*	*0.53*	*39.24*	*S.D*	*1.06*	*0.35*	*30.20*
C.V (%)	*7.08*	*1.77*	*1.05*	*C.V (%)*	*10.3*	*1.76*	*0.95*	*C.V (%)*	*5.38*	*1.34*	*0.76*

over 20 MPa for the three concrete specimens of *w/c* ratios 0.4, 0.5, and 0.6.

According to the DURAR net of CyTED program, concretes with compressive strength over 20 MPa can be considered of good quality and adequate durability for the RC structures to be built in coastal zones exposed to high (C4), very high (C5), and extreme (CX) corrosivity categories of the atmosphere [18].

On the other hand, the previous Cuban Standard established that to guarantee a high S_l of RC structures exposed to high (C4), very high (C5), and extreme (CX) corrosivity categories of the atmosphere, f_{ck} of concrete with 28 days after curing should be between 25 and 30 MPa [18]. RC structures are built under the previous Cuban Standard not only in the coastal city of Havana but also in all Cuban shorelines. Many RC structures have presented a short S_l caused by atmospheric corrosion of the reinforcement steel bars.

On the other hand, the *UPV* determined in the specimens is shown (Table 4). Following also the criteria established in the DURAR net for the concrete quality assessment, the durability and quality are adequate for concrete specimens of *w/c* ratios of 0.4, and 0.5. The average *UPV* was over 4000 m s^{-1}. In the case of concrete specimens of *w/c* ratio 0.6, the quality is classified as high. The average *UPV* determined was in the range 3001–4000 m s^{-1}.To assess the concrete quality before building the RC structure in coastal zones, many companies engaged in build in Cuba and worldwide use the measurement of *UPV*.

Results concerning the ε_e determined in concrete specimens at the three *w/c* ratios indicate an opposite situation. The criteria for the concrete quality assessment from this input basic parameter important are established too in the DURAR (Table 4). A level of ε_e indicative of good quality and compactness is shown only in the concrete specimens of *w/c* ratio 0.4. The average was lower than 10%. The quality for the concrete of *w/c* ratio 0.5 is classified as moderate. The average lies in the range 10–15%. Durability is inadequate for concrete of *w/c* ratio 0.6. The average ε_e is higher than 15%. The ε_e is a parameter not usually determined in concrete quality assessment by companies engaged in the construction in Cuba and worldwide. It will be very useful to consider the measuring of this parameter, before building RC structures in coastal zones exposed to high (C4), very high (C5), and extreme (CX) corrosivity categories of the atmosphere [23, 24].

3.4 Electrochemical corrosion rate (*I_c*)

The behavior of I_c versus time of exposure as an indicator of the atmospheric corrosion of reinforcement steel bars for RC specimens of *w/c* ratios 0.4, 0.5, and 0.6 at two concrete cover thicknesses is shown (Fig. 5a and b). Furthermore, levels of I_c in reinforcement steel in S_l terms for RC structures established in the DURAR network of the CyTED Program are shown also [18].

The I_c increases notably when the *w/c* ratio increases at both concrete cover thicknesses mainly during the second and third year of exposure (Fig. 5a and b). The increase was more significant for concrete cover thickness of 20 mm (Fig. 5a). The influence of an increase in the *w/c* ratio, as well as, the concrete cover thickness on the atmospheric corrosion of reinforcement steel is observed in the coastal outdoor exposure site. The extreme (CX) corrosivity category of the atmosphere is determined at a short distance from the sea. The atmosphere is classified as coastal-industrial.

The I_c showed a slight increase versus time of exposure for RC specimen of *w/c* ratio 0.4, and concrete cover thickness of 20 mm (Fig. 5a). A medium level of atmospheric corrosion of the reinforcement steel for RC specimen of *w/c* ratio 0.4, and concrete cover thickness of 20 mm was reached during the third year of exposure. The I_c was higher than 0.1 μA cm^{-2} (Fig. 5a).

Similar behavior was observed for RC specimens of *w/c* ratio 0.5 and 0.6 during the first year of exposure. The only one that, values of I_c were higher. This trend was maintained for RC specimen of *w/c* ratio 0.5 in the second year of exposure, coming up to a very high level in the third year of exposure. A very high level was reached faster for RC specimen of *w/c* ratio 0.6 in the second and third year of exposure (Fig. 5a).

On the other hand, the I_c was always lower than 0.1 μA cm^{-2} for RC specimen of *w/c* ratio 0.4, and concrete cover thickness of 40 mm (Fig. 5b). A negligible level of atmospheric corrosion of reinforcement steel was determined during the three years of study in the coastal outdoor exposure site. The I_c higher than 0.1 μA cm^{-2}, and sometimes in the range 0.5—1 μA cm^{-2}, were reached in the second and third years of exposure respectively, for RC specimen of *w/c* ratio 0.5 (Fig. 5b). Medium and high levels of atmospheric corrosion of reinforcement steel were determined. The I_c in the range 0.5—1 μA cm^{-2} for RC specimen of *w/c* ratio 0.6 were determined in the second and third years of exposure. Therefore, a high level was reached (Fig. 5b).

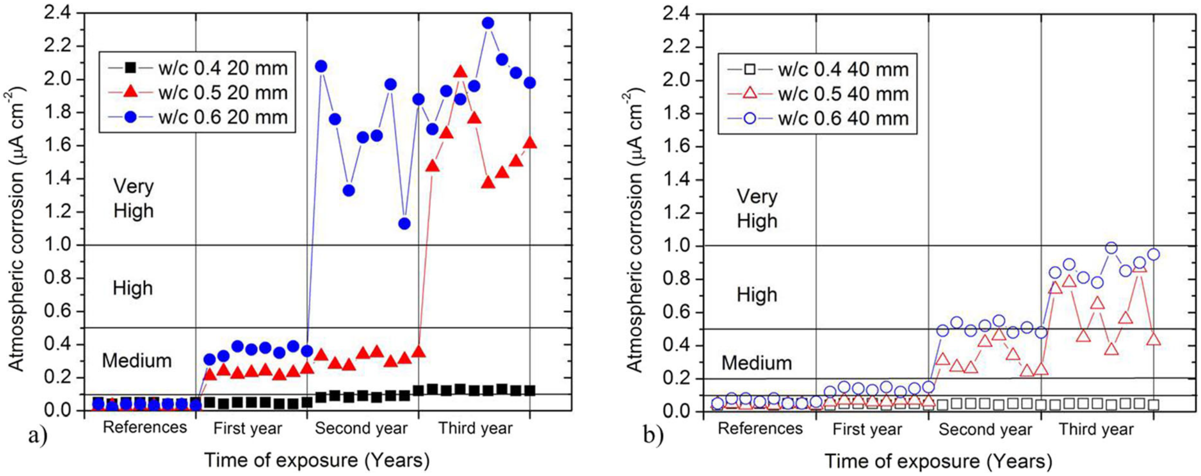

Fig. 5 Behavior of I_c versus time of exposure in the RC specimens of w/c ratios 0.4, 0.5, 0.6 and concrete cover thicknesses 20 mm (**a**) and 40 mm (**b**)

3.5 Determination of $\boldsymbol{t}_{\mathrm{i}}$ and $\boldsymbol{t}_{\mathrm{cc}}$

According to levels of I_c in reinforcement steel in S_l terms for RC structures established in the DURAR network; t_i is considered, when a medium level ($0.1 > r_{corr} > 0.5$ μA cm^{-2}) of I_c in S_l terms for the RC structures is reached (Fig. 5a and b). Atmospheric corrosion starts when the chloride ions reach the reinforcement steel surface at t_i. It should be considered in Tuutti´s model, that is to say, t_i should be established from a given level of atmospheric corrosion of the reinforcement steel (Fig. 1). On the other hand, the t_{cc} is considered when a high level ($0.5 > r_{corr} > 1.0$ μA cm^{-2}) or very high level ($r_{corr} > 1.0$ μA cm^{-2}) of I_c in S_l terms are reached (Fig. 5a and b).

Under these criteria, t_i is considered as three years in reinforcement concrete specimen of *w/c* ratio 0.4 for concrete cover thickness of 20 mm. The t_i is reached in the first year for RC specimen of *w/c* ratios 0.5 and 0.6. The t_{cc} is considered at two and three years for the same RC specimen, respectively (Table 5).Therefore, the S_l, determined from the sum of t_i plus t_{cc} of RC structures exposed to extreme (CX) corrosivity category of the atmosphere in a coastal city like Havana, and built with concrete of *w/c* ratios 0.5 or 0.6, and concrete cover thickness of 20 mm, should not exceed five years (Table 5).

The t_{cc} and t_i were not considered for RC specimen of *w/c* ratio 0.4 for concrete cover thicknesses of 20 mm, and 40 mm respectively using the measurements of I_c in RC probes in terms of S_l. This means t_i and t_{cc} are longer than the time of the experiment carried out in the study. Prediction of I_c is very necessary.

The t_i is considered one and two years in RC specimens of *w/c* ratio 0.6 and 0.5 for concrete cover thickness 40 mm. The t_{cc} is considered to reach after two and three years respectively (Fig. 5a and b). Therefore, S_l of RC structure exposed to extreme (CX) corrosivity category of the atmosphere in a coastal city like Havana and built with concrete of *w/c* ratio 0.5 and 0.6 for concrete cover thickness of 40 mm should not exceed five years (Table 5).

Concrete cover thicknesses of 20 and 40 mm does not exert a great influence on t_i, and t_{cc}, in RC specimens of *w/c* ratios 0.5, and 0.6. Very similar behavior is observed for the two concrete cover thicknesses (Table 5). A higher influence of concrete cover thickness on time is shown only for the RC specimen of *w/c* ratio 0.4, exposed to extreme (CX) corrosivity category.

According to previous Cuban Standards, concrete elaborated with *w/c* ratios of 0.5 and 0.6, and concrete cover thicknesses of 20 and 40 mm, corresponds to design conditions most used in the RC structures build in Cuba. Many RC structures have presented a short S_l, indicative of severe deterioration, caused by atmospheric corrosion of the reinforcement steel.

Average f_{ck}, *UPV*, and ε_e data determined during concrete quality characterization are shown (Table 5). The t_i and t_{cc} are determined at shorter times of exposure in RC specimens of *w/c* ratios 0.5 and 0.6, and concrete cover thicknesses of 20 and 40 mm exposed to extreme (CX) corrosivity category (Table 5). It is confirmed that, the rapid appearance of t_i and t_{cc} depends on the concrete quality.

3.6 Determination of $\mathrm{t_i}$ and $\mathrm{t_{cc}}$ from the prediction of $\boldsymbol{I}_{\mathrm{c}}$

Prediction of the I_c for the time of exposure higher three years allows the consideration of t_{cc} in the RC specimen of *w/c* ratio 0.4, for concrete cover thickness

Table 5 Time-to-corrosion-initiation, time to corrosion with induced cracking, and service life

w/c ratio	Concrete quality			Concrete covering thicknesses					
				20 mm			40 mm		
	ε_e *(%)*	f_{ck} *(MPa)*	*UPV (m s^{-1})*	t_i (Years)	t_{cc} (Years)	S_l (Years)	t_i (Years)	t_{cc} (Years)	S_l (Years)
0.4	7.06	36	4 246	3	7	10	40	∼ 14	∼ 54
0.5	13.7	30	4 106	1	3	4	2	3	5
0.6	19.7	26	3 936	1	2	3	1	2	3

of 20 mm. The I_c for times of exposure higher than three years, up to twenty years, obtained from regression fitting (3) are shown (Fig. 6a). The obtained regression fitted from the behavior of I_c versus time of exposure was:

$$I_c = 0.027t^{1.49} \quad R^2 = 91\% \tag{4}$$

In this way, the t_{cc} was considered after seven years, that is to say, when the I_c reaches a high level ($0.5 < r_{corr} < 1.0$ μA cm^{-2}) in S_l terms (Fig. 6 a). According to the sum of t_i, and t_{cc}, the S_l for RC structures built under these conditions could be around ten years in the coastal city of Havana (Table 5).

However, t_i for RC specimens of *w/c* ratio 0.4 for concrete cover thickness of 40 mm was considered after forty years. The I_c reaches a medium level ($0.1 > r_{corr} > 0.5$ μA cm^{-2}) in S_l terms. The t_i was around thirty times higher compared with the consideration for concrete cover thickness 20 mm. The influence of concrete cover thickness for RC specimen of *w/c* ratio 0.4 continues to be demonstrated. The I_c was obtained from the statistical method of the Cumulative Sum (Fig. 6 b). Considering t_{cc} for concrete cover thickness of 40 mm would be only twice as high as t_{cc} for concrete cover thickness of 20 mm (14 years). The S_l higher than fifty years could be obtained (Table 5).

4 Discussion

A total of 17 frontal systems (cold fronts) penetrated in Havana City during the winter season (October to April) corresponding to the first year of study (2008). Seven cold fronts were classified as of moderate intensity. The monthly maximum speed of the sustained wind was over 9 m s^{-1} during the winter months (November to March). Monthly$Cl^{-}DR$ was over 1000 mg m^{-2}d^{-1} (Fig. 4 a). Atmospheric corrosion of the reinforcement steel in RC structures is developed very fast in the coastal-industrial atmosphere. On the other hand, previous research work about the penetration of marine aerosol in a tropical coastal city (Havana) showed high monthly. $Cl^{-}DR$ was obtained starting from a *WS* of 3 m s^{-2} in the coastal outdoor exposure site, one of the lower *WS* thresholds worldwide. Also, related to the behavior of $Cl^{-}DR$ versus distance from the sea, it was noticed that more than 90% of the chloride salts were deposited in the coastal outdoor exposure site without shielding conditions, in the winter season [25].

Regarding other atmospheric corrosion studies carried out previously in the coastal tropical climate of Cuba, a higher annual average $Cl^{-}DR$ based on a dry plate device method was determined. The coastal outdoor exposure site was also placed at a 10 m distance from the sea, without the shielding effect caused by structures as well as, by tall and natural vegetation. The annual average $Cl^{-}DR$ was 919.3 mg m^{-2}d^{-1}. According to relation (1), the annual average $Cl^{-}DR$ estimated by wet candle device

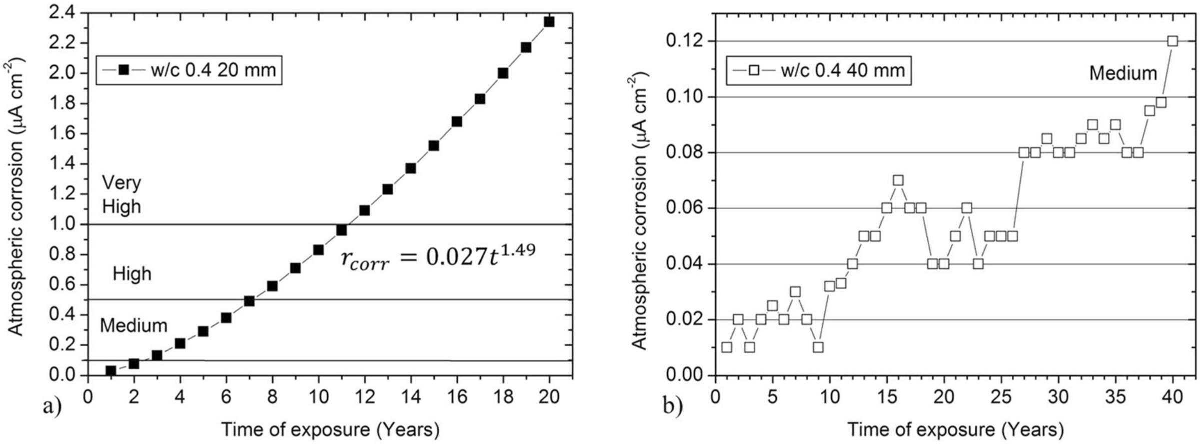

Fig. 6 Predictions of I_c vs. time of exposure in the RC specimen of w/c ratio 0.4 and concrete cover thicknesses 20 mm (**a**) and 40 mm (**b**)

method is 2206.32 mg $m^{-2}d^{-1}$ [26]. Carbon steel specimens were heavily attacked by atmospheric corrosion causing a considerable deterioration very noticeable to the naked eye (Fig. 7). Annual values of atmospheric corrosion rate (in g m^{-2}) were around 5 500 g m^{-2}.

Very few reports have been found in coastal cities worldwide, where the annual average $Cl^{-}DR$ determined or estimated by wet candle device is over 2040 mg $m^{-2}d^{-1}$(850 mg $m^{-2}d^{-1}$determined by dry plate device method), and 2206.32 mg $m^{-2}d^{-1}$. The annual average $Cl^{-}DR$ determined in the coastal cities of Sriharikota, India, and Tuxtla, Mexico was 3378 mg $m^{-2}d^{-1}$ and 5000 mg $m^{-2}d^{-1}$, respectively [27, 28].

In the MICAT project (Ibero-American Map of Atmospheric Corrosivity) in which 14 countries of the Ibero-American region participated, 75 coastal outdoor exposure sites were placed [29]. The highest annual average $Cl^{-}DR$ using the wet candle device method was 1909 mg $m^{-2}d^{-1}$ determined in the coastal city of Sherman, Panama.

Regarding the DURACON project, the highest annual average $Cl^{-}DR$ using the wet candle device method was 1392 mg $m^{-2}d^{-1}$ determined in the coastal city of Cabo Razo, Portugal.

Therefore, the coastal city of Havana, could be considered one of the most aggressive of the Ibero-American region. Many RC structures exposed to the direct influence of marine aerosols present generally a severe deterioration indicative of short S_l, due to the increase of atmospheric corrosion of the reinforcement steel bars. In this way, calculate the expected S_l of RC structures built, and those intended to be built, in a coastal city like Havana, is an important coastal management parameter. On the other hand, the atmospheric transitory processes influencing in the corrosivity category of the atmosphere such as $Cl^{-}DR$, $SO_x^{-}DR$, RH, T, and WS, should be included in the software as input basic parameters. Furthermore, concretes with very high quality are required to be used in RC structured buildings.

According to the average f_{ck}, and UPV, the three concrete specimens prepared with *w/c* ratios of 0.4, 0.5, and 0.6, RC structures exposed to extreme (CX) corrosivity category of the atmosphere, could show an extension in S_l. Concrete prepared with *w/c* ratios of 0.5 and 0.6 could be durable in the coastal city of Havana. However, t_i and t_{cc} were reached quickly in RC specimens with concrete cover thicknesses of 20 mm and 40 mm, placed at the coastal outdoor exposure site. The concretes presented ε_e of 13.7% and 19.7%, respectively (Table 4). The concrete quality is moderate for a *w/c* ratio of 0.5. Durability is inadequate for a *w/c* ratio of 0.6.

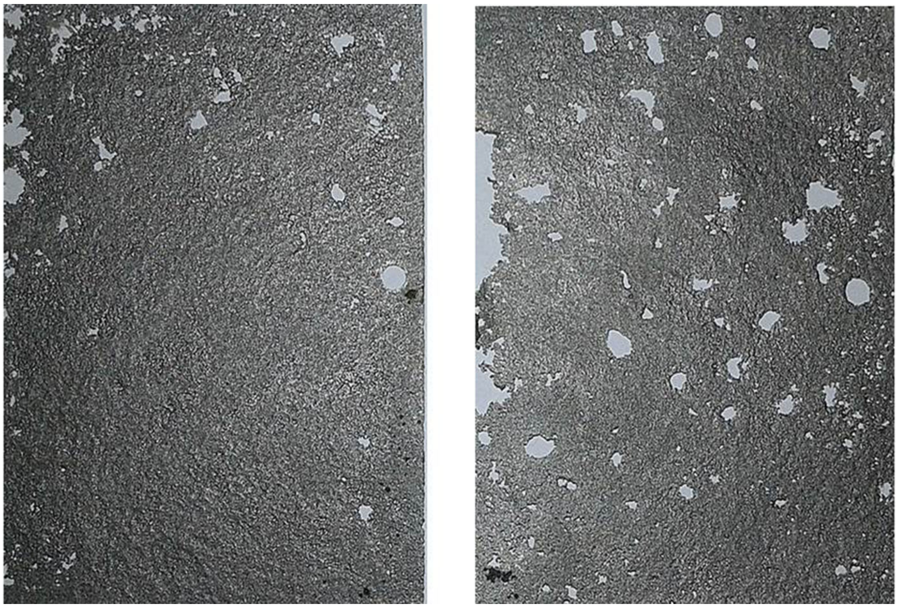

Fig. 7 Carbon steel specimens were heavily attackedbyatmospheric corrosion

The f_{ck} and *UPV* are important parameters, but the information is not enough concerning concrete quality characterization for RC prepared with w/c ratios 0.5, and 0.6. The ε_e should be determined as a deeper factor for concrete quality characterization for previous building works in coastal cities at short distances from the sea. Nevertheless, f_{ck} *UPV*, and ε_e, which influence in the concrete quality, should be considered as input basic parameters in the software and models to predict with higher accuracy and precision the S_l in RC structures in coastal cities.

The I_c as an indicator of the atmospheric corrosion of reinforcement steel, presented a slight increase during the time of exposure for RC specimen of *w/c* ratio 0.4, and concrete cover thickness of 20 mm (Fig. 5a). The result of the regression fitted (4) presents a constant *b* higher than 1. Therefore, a significant increase in the corrosion rate is also shown for RC specimens of *w/c* ratio 0.4, and concrete cover thickness of 20 mm. A S_l around of ten years for RC structures built under the conditions of extreme (CX) corrosivity category of the atmosphere, and atmosphere classified as coastal-industrial is not high. S_l of RC structures of over fifty years should be obtained (Table 5).

The results obtained (Table 5) can be considered an useful parameter for coastal management model to be obtained, in order to build RC structures under the conditions of extreme (CX) corrosivity category of the atmosphere, and for atmospheres classified as coastal-industrial, not only for a coastal city like Havana.

The induced cracking, caused by atmospheric corrosion of the reinforcement steel is detected after the third year of study in RC specimens of *w/c* ratios of 0.5 and 0.6 for both concrete cover thickness (Fig. 8a and b).

The cracking is more noticeably for concrete cover thickness of 20 mm. However, induced cracking appeared at two years (t_{cc}) in the RC specimens of *w/c* ratio 0.6 for both concrete cover thicknesses. The Software, actualized in the S_l studies, does not consider the induced cracking, caused by atmospheric corrosion of the reinforcement steel bars in the RC.

The influence of the *w/c* ratio increase as well as, the concrete cover thickness in the atmospheric corrosion of reinforcement steel bars in RC, is confirmed in the coastal outdoor exposure site. Higher penetration of the aggressivity agents, mainly the chloride ions is provoked by the induced cracking. RC with *w/c* ratios 0.5, and 0.6, as well as concrete cover thicknesses of 20 mm and 40 mm, do not ensure suitable primary protection as a physical barrier. The induced cracking confirms that S_l for the RC structures exposed to extreme (CX) corrosivity categories of the atmospheres, does not exceed five years. Hence, RC with w/c ratios 0.5 and 0.6 and with concrete cover thicknesses of 20 mm and 40 mm cannot be used in the building works of RC structures in the coastal city of Havana.

The visual observation in the RC specimens allows confirming that, the engineers need to know with high level of accuracy the S_l in RC structures located in coastal cities, and exposed to the direct influence of marine aerosols as a parameter for effective coastal management. In this way, Cuba already has its effective tools, included in the standards, that allow the determination (Table 5) and prediction (Fig. 6a and b) of S_l in RC structures, before proceeding with building work in cities and coastal zone. In spite of, concrete cover thickness and *w/c* ratio are requirement very necessary in the concrete quality, atmospheric corrosion of reinforcement steel in the time of exposure play a good role to obtain S_l in the RC structures for a long time.

Recently, a correlation between concrete cracking and corrosion of reinforcement steel in two natural marine environments of tropical coastal climate of Mexico was presented. The relevant variable in the atmospheric corrosion of reinforcement steel was the *w/c* ratio [30]. Behaviour of atmospheric corrosion of reinforcement steel bars in the time of exposure was not considered.

5 Conclusions

The S_l of RC structures in extremely coastal site of a city like Havana, considered one of the most aggressive environments of the Ibero-American region, depends on concrete quality, and atmospheric corrosion of reinforcement steel. Changes in the *w/c* ratio and concrete cover thickness, determined significant changes in the atmospheric corrosion rate of reinforcement steel in RC specimens exposed to extreme (CX) corrosivity categories of the atmosphere. The role of concrete cover thickness with respect to the S_l in RC structures become important for 0.4 *w/c* ratio.

Fig. 8 Visual observation of the RC specimens placed in the coastal outdoor exposure site during three years of study

Prediction and determination of the I_c, as indicator of atmospheric corrosion of reinforcement steel bars in RC specimens exposed in a coastal outdoor exposure site, can be used to obtain t_i plus t_{cc}. The importance of obtaining t_i from the prediction and determination of I_c in the reinforcement steel is confirmed in the research work.

To follow the RC degradation process from the behavior of the atmospheric corrosion of reinforcement steel bars and to calculate the expected S_l from the measurement of the I_c at the time of exposure in RC specimens, is recommended as a very useful parameter. The I_c in RC specimens exposed to extreme (CX) corrosivity category of the atmosphere represents the magnitude of the atmospheric corrosion of the reinforcement steel bars.

Effective capillary porosity is an important parameter required in the concrete quality assessment before building RC structures exposed to extreme (CX) corrosivity categories of the atmosphere. In addition f_{ck} and UPV are also important parameters but the information is not enough concerning concrete quality characterisation.

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Declarations

Conflict of interest The authors declare that they have not known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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