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Durability of concrete structures: DURACON, an iberoamerican project. Preliminary results

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Abstract

This work presents preliminary results of the international project: "Effect of the environment on reinforced concrete durability: DURACON", which shows the physical, mechanical and chemical characterization of two different concrete mixtures prepared in the participating countries, as well as the environment to which the specimens are exposed. These results show the potentiality and probability of future reinforcement corrosion, depending on the type of mixture and the environment to which the structure is exposed. To that effect, concrete specimens, with and without reinforcement, were prepared for electrochemical and physical/mechanical/chemical testing using the existing materials in each participating country, following premises that enabled the preparation of similar concrete specimens. Two water/cement ratios (0.45 and 0.65) were selected, where the concrete with $w/c = 0.45$ had to have a minimum cement content of $400\,kg\,m^{-3}$, and the other with $w/c = 0.65$, a minimum compressive strength of 21 MPa. Ordinary Portland Cement (OPC), crushed coarse aggregate, and silica sand were used for concrete preparation. The specimens were exposed to several microenvironments including urban and marine conditions (at least two testing sites in each country), resulting into a total of 46 test sites distributed among 11 countries (Argentina, Bolivia, Brazil, Chile, Colombia, Costa Rica, Mexico, Spain, Uruguay, Portugal, and Venezuela). The environment was evaluated using ISO Standard 9223 and the concrete was characterized by measuring compressive strength, modulus of elasticity, total and effective porosity, and rapid chloride permeability according to ASTM standards, as well as resistance to water absorption, using the Fagerlund method.

After 1-year exposure, some results of the corrosion potentiality and probability analysis of the reinforcement in several test sites based on environmental meteorochemical parameters show that, for specific microclimates like those in marine atmospheres, the most aggressive environment is that at Cabo Raso test site in Portugal, inducing the greater steel-corrosion probability. The least aggressive is the one at Valparaíso in Chile. It was also determined that Maracaibo, Venezuela, is the one that has the greatest probability of early rebar corrosion initiation by carbonation, with the test site at Cali, Colombia being the one that would induce the least corrosion probability.

Keywords: Reinforced concrete; Environmental factors; Atmospheric corrosion; Carbonation; Chloride ion diffusion

1. Introduction

Originally, it was thought that the service life of reinforced concrete as a building material was unlimited. However, premature deterioration caused by reinforcement corrosion is being reported in an increasing number of structures. In general, this corrosion is caused by the destructive attack of chloride ions penetrating by diffusion and/or other penetration mechanisms from the outside, by incorporation into

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the concrete mixture, by carbonation of the concrete cover of the reinforcement or a combination of them.

Research on reinforcement corrosion is driven by the quest for a methodology that would provide a precise and correct answer to what causes corrosion. Corrosion is causing heavy losses worldwide. For example, half of the 575,000 bridges in USA are corroded by deicing salt spread on the roads in winter, and at least 40% have been considered structurally deficient [1]. Interstate repair costs are estimated at US$50 billion, a figure that is constantly rising. Similarly, the bridges on highways in the UK require attention because they have also been severely corroded by deicing salt [2]. Repair costs are estimated at more than 620 million pounds over the next 10 years. No definitive economic information is available for Ibero-America. One would expect less corrosion than in cold countries, where abundant salt is used in winter. In relative terms, however, its economic impact is very important. The results of technical evaluations carried out in these countries show that damage due to reinforcement corrosion is among the first three causes of deterioration in concrete structures. Specifically, Spanish Concrete Group (GEHO) in Spain analyzed 844 cases with different pathologies, with reinforcement corrosion taking third place as the most frequently occurring pathology among the problems detected [3]: 15% as compared with 2% and 22% for cracking and load deformation, respectively. In southern Brazil, a detailed analysis of 1512 cases of diagnoses with different pathologies carried out by Dal Molin [4] showed that the incidence of corrosion in the reinforcement represents 40% of total damage. Other studies performed in Brazil on numerous structures in marine and industrial environments, indicated that reinforcement corrosion is the main cause of deterioration, representing between 20% and 58% of the cases [5–8].

It must be pointed out that the quality and duration of repairs in reinforced concrete structures depend on the correct evaluation and diagnosis of the problem, based on appropriate inspection procedures. Numerous organizations, such as PCA [9], NMAB [10], SHRP [11], ACI [12], ASTM [13], NACE International [14], RILEM [15] and CEB [16], have been working consistently in an effort to document this subject. However, since there is not a general consensus, inspections had been carried out in many different ways. Sometimes inadequate repairs and disordered rehabilitation expenses to the owners of the damaged infrastructure are the final results.

Aware of the difficulties involved in solving these corrosion related problems, in 1993 CYTED (Science and Technology for Development Program, Spain), within the XV Subprogram (SP XV) "Corrosion and Environmental Impact on Materials", formed a Thematic Network for Reinforcing Bars (rebars) Durability, called DURAR, at an Ibero-American level, gathering concrete-corrosion specialists from Argentina, Brazil, Colombia, Cuba, Spain, Mexico, Peru, Portugal, Uruguay and Venezuela. The general objective of DURAR, was to gather and exchange ideas, experiences, and research results among all these specialists, and to integrate a manual for inspection, testing and evaluation methods and criteria to enable the use of better intervention, repair and rehabilitation systems for reinforced concrete structures deteriorated by corrosion. Thus, a procedure manual [17] (both in Spanish and in English languages) was prepared in order to unify the evaluation criteria and methods for diagnosing reinforced concrete structures deteriorated by corrosion. Twenty-seven courses have been given, and most of the people dealing with this problem in the Ibero-American countries are using this manual to solve corrosion problems in reinforced concrete structures. After 7 years, DURAR has encouraged and integrated joint actions in Ibero-American institutes, including universities and private construction and structure repair companies.

Continuing the DURAR Network, "The Influence of Environmental Action on Reinforced Concrete Durability: DURACON" project was approved in year 2000, with the participation of 11 countries. The aim of this project is to characterize the durability of concrete exposed to prevailing environmental conditions in Ibero-America, using some of the test sites from previous studies performed by CYTED [18]. The project is based on the exposure of reinforced and non-reinforced specimens at several microclimates (at least two different atmospheres: marine and urban) in each participating country. Two types of concrete specimens were prepared, with and without steel reinforcement, and with water-to-cement (w/c) ratios of 0.65 and 0.45. The tests are concentrated mainly on characterizing the carbonation and chloride penetration processes, determining the chloride corrosion threshold and measuring electrochemical parameters that would enable the evaluation of reinforcement corrosion kinetics.

The different varieties of climate/microclimates in Ibero-America will permit an environment characterization that would induce corrosion in the reinforcement and have an effect on reinforced concrete structural performance. In the future this project will allow the identification of chloride thresholds for corrosion in a wide variety of microclimates and in addition to some of them previously reported in Latin-America [19–21].

Determining the chloride ion threshold to induce rebar corrosion, and the rate of concrete carbonation as a function of concrete quality, along with the environmental factors (relative humidity, time of wetness, temperature, chlorides content, CO_2, etc.) typical of each region, will help designing durable reinforced concrete for engineering projects, as well as with implementing adequate repair procedures for existing ones. This will be the first abundant environmental data gathering that will lead to a statistical analysis using tropical environments data. Forty-six testing sites with the most aggressive tropical environments will be evaluated to establish the threshold chloride concentrations. So far the present authors consider the use of 0.4 wt% free chloride concentration based on cement content as the corrosion threshold onset, yet other researchers have used this value as total chloride concentration. The later is an over-rated estimation, since experimental data from real marine structures have shown total chloride thresholds exceeding 1 wt% [21,22]. Therefore, establishing the adequate chloride criteria, which depends on the environmental parameters of a specific region, will lead to a substantial improvement of the structural performance and reliability of concrete structures, either under design, repair or currently functional.

The main objectives of this multi national project are: to correlate concrete durability with environmental characteristics; to estimate the chloride threshold onset that induces corrosion on rebars, based on the different environmental conditions; and, to propose models to predict service life according to the different micro-climates/atmospheres tested.

This paper presents the preliminary results obtained by DURACON based on the gathered results in the different countries where the project is being held, during the first year of specimen exposures. The environment corrosivity analysis was made based only on environment parameters data. A detailed analysis of chloride threshold and carbonation degradation will be presented in a future publication of this project.

2. Experimental procedure

2.1. Materials characterization

The following tests were performed to characterize physically and mechanically the concrete mixtures, with w/c ratio of 0.45 and 0.65, in each country involved:

- Compressive strength at 28 and 90 days (ASTM Standard C 39). Indirect resistance to stress at 28 days (ASTM Standard C 496)
- Modulus of elasticity at 28 days (ASTM Standard C 469)
- Resistivity (in saturated specimen/Manual DURAR [17])
- Total absorption and total porosity (ASTM Standard C 642)
- Capillary absorption (Fagerlund Technique) [23]
- Rapid chloride permeability (ASTM C 1202).

These tests were performed using 15×30 cm cylinders cast at the same time the prisms were prepared.

2.2. Sample preparation

Twelve concrete prisms, $15 \times 15 \times 30$ cm, were prepared to be placed on each exposing site, six were plain, non-reinforced concrete prisms, and the remaining six were reinforced with six # 3 rebars (9.5 mm in diameter). The rebars were placed into the prisms to have concrete covers of 15, 20 and 30 mm. Fig. 1 shows the geometry of the concrete prisms used in this investigation. Fig. 2 shows a typical test site in which the different test specimens are on display.

The non-reinforced prisms were used for concrete's physicochemical tests such as carbonation front, chloride concentration profiles, and electrical resistivity under water-saturation conditions. The reinforced prisms were used for electrochemical tests such as half-cell potentials, corrosion rate, and concrete electrical resistivity.

2.3. Environmental parameter tests

Evaluation of the climatic and environmental parameters in each of the exposure sites during the test period was based on the methodology established by ISO Standard 9233 for classifying atmospheric aggressiveness. The most important parameters used in this investigation to classify the environments were environmental humidity, time of wetness (TOW/ τ), chloride concentration, sulfate concentration, wind speed and direction, pluvial precipitation, temperature, and CO_2 concentration. This meteorological and chemical evaluation of the environment's exposure sites was determined in most of the cases every month.

2.4. Chemical tests using the non-reinforced concrete prisms

To determine the chemical alteration of the concrete due to the exposed environment, the non-reinforced prisms were analyzed on a yearly basis. The procedure was slicing a 5-cm thickness rod from each of the non-reinforced concrete prisms (Figs. 2 and 3) using a custom made special devise (guillotine). The new freshly cut face, remaining in the prisms, was protected with epoxy paint. The carbonation front was measured on cut rod (15×15 cm) using a wet pH indicator as explained elsewhere [17]. The chloride concentration analysis was performed using two 2.5-cm $\varnothing$ cores extracted from the center of the sample, located at 3 cm from the lower border of the slice (Fig. 3). The cores were sliced, crushed and powdered to perform an acid-based chloride extraction, to obtain the total chloride concentration, and a water-based chloride extraction to obtain the unbound (free) chloride concentration [17].

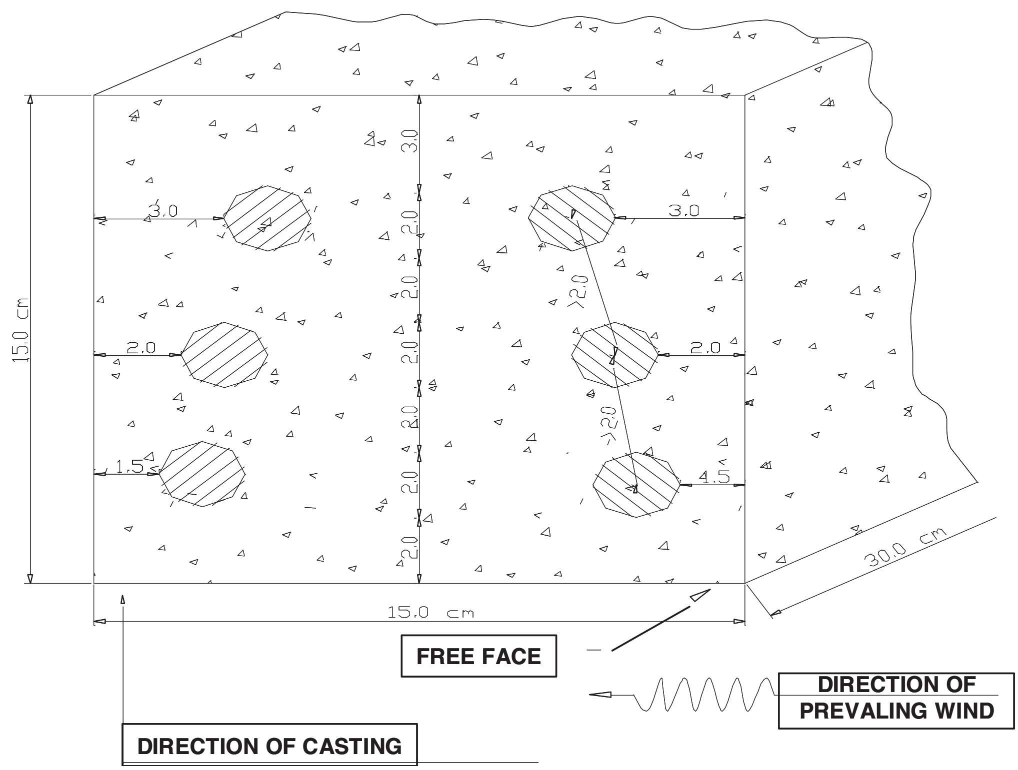

Fig. 1. Sketch of the prismatic specimen for electrochemical measurements.

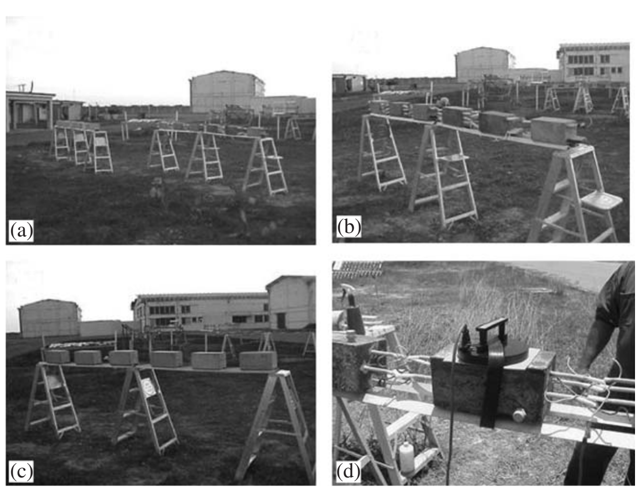

Fig. 2. Typical test station: (a) general view, (b) reinforced prismatic specimens, (c) specimens for physicochemical tests and (d) electrochemical measurements.

2.5. Corrosion parameters tests

Electrochemical parameters evaluation, half-cell potential (Ecorr), corrosion rate (icorr) and concrete electrical resistivity (ρ) were determined monthly, using the reinforced prisms. The corrosion rate was measured by the polarization resistance technique [17]. The specimens were set up with one of the 15×30 cm faces toward the prevailing winds and the other in the opposite direction (Fig. 1). The electrochemical evaluation was carried out on both faces. The cast face of the prism, showing the higher porous content, was placed downwards to avoid preferential ingress of aggressive agents from the environment.

3. Results and discussion

3.1. Physical–mechanical characterization of the concrete used in each country

Tables 1–4 show the characterization of the different types of cement and concrete prepared in each country involved in this project. It must be noted that, although an attempt was made to use the same Portland cement type I and aggregates, the final composition is different in each country, which may affect concrete quality, both from the mechanical and durability standpoints. Note that in Table 1, showing the composition of the cement types used, the tricalcium aluminate (C_3A) content is generally similar (5–8%), except for the cement from Venezuela and Spain, with contents of 10% and 0.4%, respectively. If all the concrete mixtures had the same physical characteristics, the Venezuelan concrete would be expected to provide the best protection for the rebar since, as it is well known [24], C_3A can react with chloride ions to form Friedel salt, thus reducing the free-chloride level. The same reasoning would lead us to

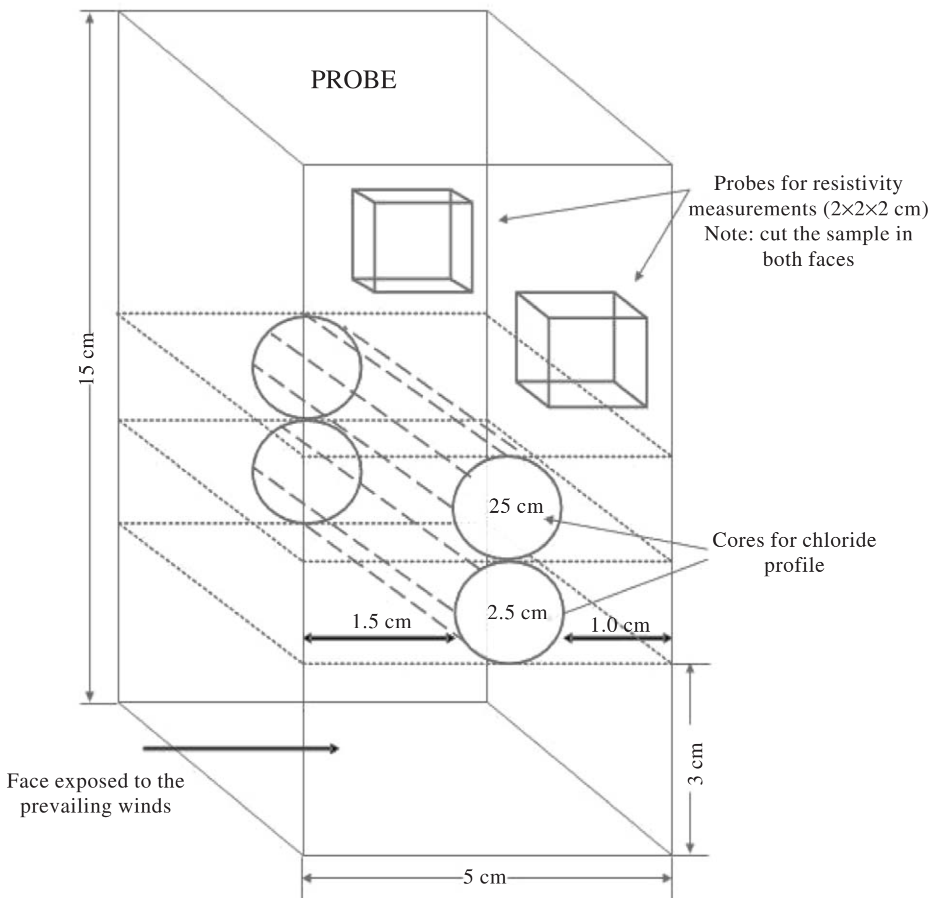

Fig. 3. Five centimeter thick slice for the physicochemical analysis.

Table 1
Chemical composition of ordinary Portland cement used

Country	Characterístics														
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	Specific surface ($m^2\,kg^{-1}$)	Free lime	C_3S	C_2S	C_4AF	C_3A	Pozz
Argentina	21.90	3.88	4.98	61.52	1.38	0.10	0.81	1.82	330	—	—	—	—		—
Bolivia	33.14	6.76	2.68	47.68	1.51	0.82	2.18	2.10	333	1.67	57.52	19.23	9.82	7.70	26.0
Brazil	18.8	5.13	2.79	57.30		0.19	1.11	3.02							
Colombia (1)	20.48	4.46	3.75	62.22	1.51	0.19	0.22	1.93	321	0.91	62.76	13.06	11.32	5.73	
Colombia (2)									410		49.21	24.49	11.43	5.45	
Costa Rica															
Chile	21.50	4.60	3.30	62.00	2.70	0.20	0.40	2.20	360		66.00	16.00	11.14	6.60	29.7
Spain	20.20	2.37	4.10	65.84	1.85	0.11	0.65	3.80		1.50			12.48	0.40	
México	21.38	4.22	4.54	63.37	1.51	0.16	0.53	2.32			54.00	20.50	13.80	3.50	
Portugal	20.26	5.35	3.42	62.17	1.88	0.11	0.98	2.68			50.61	19.87	10.41	8.39	–
Uruguay	21.66	3.12	3.32	64.86	3.46	0.04	0.19	1.63	343		69.08	9.99	10.10	2.65	
Venezuela	20.27	4.48	2.95	64.39	0.85		0.43	2.10	358	1.22	54.99	18.26	7.36	10.72	

expect that Spanish concrete could provide the least protection. However, the C_3A content is not the only important factor but the permeability of the concrete and, specifically, its capillary porosity, which indicates its capacity to resist the penetration of water and therefore, aggressive agents. Table 3 shows that the $w/c = 0.45$ concrete mixture prepared in Venezuela is the one with the highest capillary absorption (in the

Table 2
Concrete mixture proportions

Country	w/c = 0.65 Content (kg m^{-3} concrete/proportion)					w/c = 0.45 Content (kg m^{-3} concrete/proportion)				
	Cement	Water	Coarse	Sand	Additive	Cement	Water	Coarse	Sand	Additive
Argentina	295/1	192/0.65	940/3.18	900/3.05		400/1	180/0.45	880/2.20	900/2.25	
Bolivia	305/1	198/0.65	869/285	1092/3.58	—	400/1	180/0.45	952/2.38	751/1.88	3.2/0.008 Plastiment FF-86
Brazil	302.54/1	196.65/0.65	1046.79/3.46	701.89/2.32	—	437/1	196.65/0.45	1136.20/2.6	655.5/1.5	—
Colombia (1)	335/1	217.75/0.65	996.73/2.975	883.96/2.64	—	400/1	180/0.45	1013.91/2.535	899.12/2.25	6.04/0.0151 (MBT Pozzolith 430-R)
Colombia (2)	306/1	199/0.65	1021/3.33	942.50/3.08	—	400/1	180/0.45	1091.1/3.34	823.1/2.52	3.2/0.008 (Sikament)
Costa Rica										
Chile	323/1	210/0.65	911/2.82	911/2.82		387/1	174/0.45	929/2.40	929/2.40	4.64 Plastiment FF-86
Spain	300/1	195/0.65	1144/3.81	820/2.73		400/1	180/0.45	949/2.37	911/2.28	2 L m^{-3} Melcret 222 Bettor MBT
Mexico	285/1	185/0.65	1033/3.62	812/2.84		411/1	185/0.45	1010/2.45	731/1.77	2 L m^{-3} Sikament 190CR
Portugal	260/1	169/0.65	895/3.44	1003/3.86	2.5/0.0[a] Rehobuild 1000	400	180/0.45	763/1.91	970/2.42	4.8/3.3[a] Rehobuild 1000
Uruguay	323.8/1	210.4/0.65	780/2.41	948.6/2.93		400/1	180/0.45	780/1.95	865/2.16	3.2
Venezuela	355.41/1	231/0.65	1150.48/3.237	602.23/1.694	—	414.28/1	186.43/0.45	1267.96/3.61	556.86/1.34	195cc/100 kg Pozzolith 322-N

[a]New mixture.

Table 3
Characteristics of the w/c = 0.45 concrete mixtures

Country	Characteristics												
	Compressive strength (MPa)		Modulus of elasticity (GPa)	Resistivity ρ (KΩ cm)	Indirect resistance to stress (MPa)	Total absorption (%)	Total porosity (%)	Capillary absorption k (kg m^{-2} s$^{-1/2}$)	Resistance to water penetration m (s m^{-2})	Effective porosity ε (%)	Capillary sorption S (m s$^{-1/2}$)	Unit weigth (kg m^{-3})	Chloride permeab. ASTM C1202 (coul)
Time (days)	28	90	28	28	28	28	28	28	28	28	28		28
Argentina	39.80	44.30	37.90	11.50	4.17	2.80	10.04	0.018	3.17×10^7	10.13	1.77×10^{-4}	2360	—
Bolivia	26.63	30.05	23.65	6.11	2.43	7.46	17.42	0.0054	3.21×10^7	3.05	1.77×10^{-4}	2402	—
Brazil													
Colombia (1)	62.02	65.17	30.90		5.42	3.39	8.21	0.0060	15.26×10^7	7.40	8.10×10^{-5}	2493	2757
Colombia (2)	52.33	53.20	25.70		4.91	3.79	9.11	0.0066	10.70×10^7	6.80	9.70×10^{-5}	2494	3637
Costa Rica													
Chile	43.6	44.70	26.30	8.88	2.78	2.44	8.95	0.027	2.50×10^7	13.50	2.00×10^{-4}	2419	—
Spain	43.24	59.32	35.32	8.12	3.21	4.70	9.99	0.0054	10.50×10^7	5.28	9.80×10^{-5}	2440	3720
México	51.48	67.86	22.45		3.57	6.3	13.95	0.0142	3.64×10^7	8.50	1.67×10^{-4}	2329	—
Portugal (1)	48.75	53.75	23.79	9.70	2.27		13.11	0.0089				—	4223
Portugal (2)	63.9	70.6	29.9	10.5	—	—	12.9	0.0020				—	3377
Uruguay	45.2	42.50	31.05	4.40	3.04	5.24	11.8	0.0196	3.3×10^7	11.25	1.7×10^{-4}	2473	4608
Venezuela	33.82	39.65	26.07	7.03	4.43	6.71	15.25	0.0082	8.68×10^7	7.63	1.03×10^{-4}	2425	4569

Table 4
Characteristics of the w/c = 0.65 concrete mixtures

Country	Characteristics												
	Compressive strength (MPa)		Modulus of elasticity (GPa)	Resistivity ρ (KΩ cm)	Indirect resistance to stress (MPa)	Total absorption (%)	Total porosity (%)	Capillary absorption k ($kg\,m^{-2}\,s^{-1/2}$)	Resistance to water penetration m ($s\,m^{-2}$)	Effective porosity ε (%)	Capillary sorption S ($m\,s^{-1/2}$)	Unit weight ($kg\,m^{-3}$)	Chloride permeab. ASTM C1202 (coul)
Time (days)	28	90	28	28	28	28	28	28	28	28	28		28
Argentina	22.30	27.30	27.20	8.09	2.20	5.10	12.76	0.0290	2.00×10^{7}	12.97	2.20×10^{-4}	2327	—
Bolivia	16.81	17.95	15.70	4.31	1.82	9.35	21.53	0.0200	2.12×10^{7}	9.2	2.17×10^{-4}	2346	—
Brazil													
Colombia (1)	36.10	38.50	22.50	5.88	3.56	4.66	11.22	0.0122	7.28×10^{7}	10.40	1.17×10^{-4}	2433	4178
Colombia (2)	28.01	30.28	18.90	5.93	2.96	4.91	11.79	0.0085	4.50×10^{7}	8.06	1.49×10^{-4}	2468	4044
Costa Rica													
Chile	19.80	26.00	19.10	6.20	1.94	5.21	17.02	0.0341	2.25×10^{7}	16.13	2.11×10^{-4}	2355	7339
Spain	27.00	34.36	28.47	8.01	2.63	3.90	13.39	0.0092	6.10×10^{7}	7.15	1.30×10^{-4}	2459	5586
México	30.99	41.58	18.10		1.17	7.55	16.45	0.0201	3.01×10^{7}	11.02	1.82×10^{-4}	2316	—
Portugal (1)	32.75	37.00	27.27	9.80	2.64		12.60	0.0077				2327	7585
Portugal (2)	35.4	38.7	24.6	10.0	—	—	13.50	0.0079	—	—	—	2327	3695
Uruguay	28.94	34.96	27.94	3.7	2.42	6.45	14.00	0.0267	3.2×10^{7}	15.10	1.8×10^{-4}	2433	9179
Venezuela	26.80	30.80	23.50	5.22	3.49	8.93	19.15	0.0253	3.74×10^{7}	15.41	1.65×10^{-4}	2340	4974

order of $0.0082\,kg\,m^{-2}\,s^{-1/2}$) which indicates a greater potentiality of aggressive-agent ingress. The same occurs with w/c = 0.65 cement mixtures (Table 4), in which the Venezuelan concrete showed the highest absorption capacity of all mixtures prepared.

3.2. Characterization of the different exposure environments

ISO Standard 9223 classifies the atmosphere in accordance with TOW and the deposition rate of atmospheric pollutants: sulfur compounds (P) and salinity (S) [25]. Fig. 4 attempts to show expected relative aggressiveness at the different test sites analyzed. However, considering that the sulfur dioxide content in the atmosphere does not affect reinforcement corrosion, as would carbon dioxide and chloride ions do, CO_2 instead of SO_2 content is ploted as the "*Y*" axis of Fig. 4.

Fig. 4 shows the preliminary results from most of the test sites, which have at the moment undergone evaluation for 1 year. In this figure, both CO_2 and chloride ions are the parameters considered for environmental corrosion potentiality. Note the wide range of environments, from low to very high corrosivity, taking chloride content in the atmosphere into consideration for the particular case of the concrete specimens exposed to the marine atmosphere. In urban atmospheres, the most important contaminant will be CO_2, which will be discussed further on. Tables 5 and 6 show the yearly averages for the meteorological and chemical variables and the ISO 9223 classification for the marine environments in some of the test sites that have undergone 1 year of evaluation. It can be seen that, from high to low, the aggressivity order would be: Portugal (Cabo Raso), Venezuela (La Voz), Spain (Vigo), Colombia (Buenaventura) and Chile (Valparaíso).

For urban environments, Table 7 shows the different parameters (yearly averages) that would enable the aggressiveness of this environment to be evaluated from the CO_2 [17] content standpoint. Relative humidity is very important, but above all the TOW fraction, by means of which the percentage of time a naked plate would remain wet during one year.

There must be low RH (<80%) for concrete to be carbonated, since this leaves the pores empty enough for CO_2 to penetrate the concrete easily. The presence of high humidity (>80%) is important for a reinforcement to corrode in an already carbonated concrete, so the frequency of rain is an additional parameter to be considered. In carbonated concrete, in which the reinforcement loses passivity, the reinforcement behaves like steel with inadequate coating, so there must be high RH for it to start corrosion [17]. Therefore, jointly analyzing the potentiality of these parameters to cause reinforcement corrosion (CO_2 and TOW), the

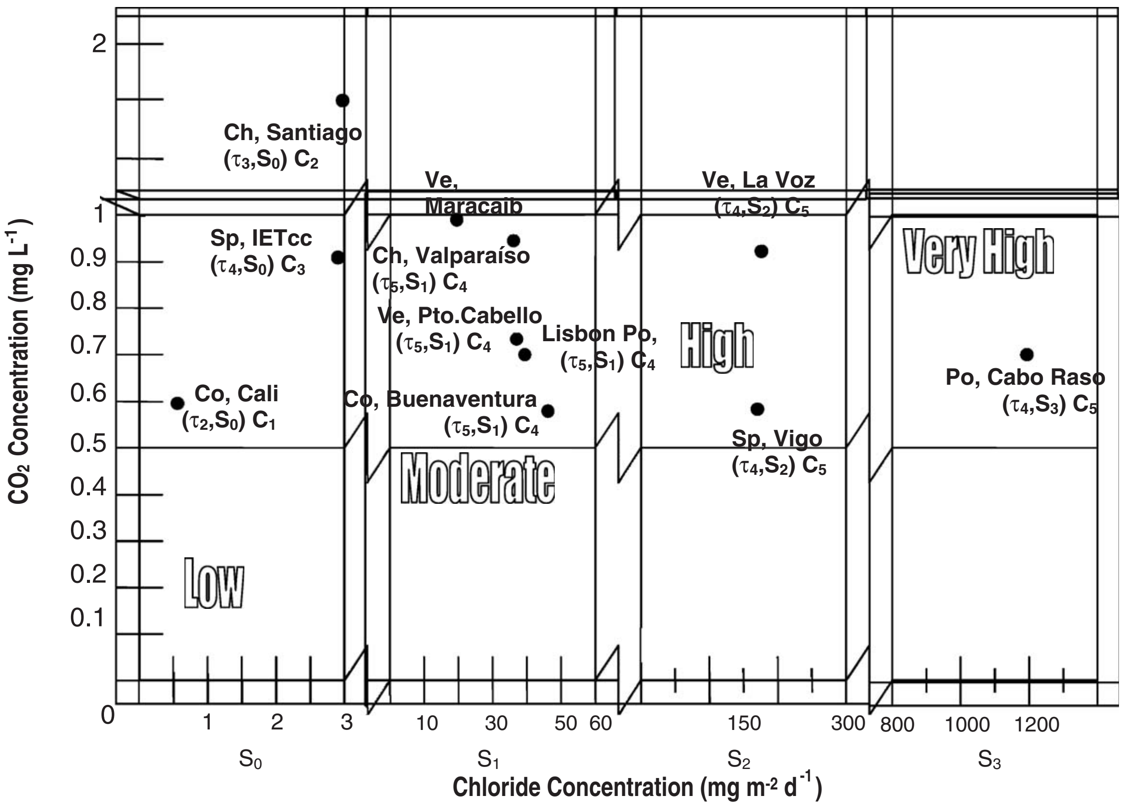

Fig. 4. Environmental corrosivity (ISO 9223).

Table 5
Environmental and concrete characteristics (w/c = 0.45) from selected marine sites for potential estimation of corrosion onset of steel in concrete by chloride penetration

Country (station)		Portugal (cabo raso)	Venezuela (La Voz)	Spain (Vigo)	Colombia (1) (Buenaventura)	Colombia (2) (Buenaventura)	Chile (Valparaiso)
Enviroment (yearly average)	RH (%)	77.0	90.0	69.0	89.2	89.2	82.8
	TOW fraction $f(\tau)$	0.58	0.67	0.31	0.89	0.89	0.70
	Temp. (°C)	14.1	29.35	15.8	25.9	25.9	15.3
	Cl^- ($mg\,m^{-2}\,d^{-1}$)	1215	166.52	156.21	29.0	29.0	19.26
	Rain ($mm\,year^{-1}$)	140.2	398	1267.6	6581	6581	500
w/c = 0.45							
fc_k(MPa)/28days		48.75	33.82	43.24	62.02	52.3	43.6
C_3A		8.39	10.72	0.40	5.73	5.45	6.6
ε (%)			7.22	5.28	7.40	7.40	13.4
m ($s\,m^{-2}$)			3.71×10^7	10.5×10^7	15.26×10^7	10.7×10^7	2.50×10^7
k ($kg\,m^{-2}\,s^{-1/2}$)		0.0020	0.0082	0.0054	0.0060	0.0066	0.0027
Cement content ($Kg\,m^{-3}$)		400	414.3	400	400	400	387

aggressiveness order of these environments from high to low would be: Venezuela (Maracaibo), Chile (Santiago), Spain (IETcc), Portugal (LNEC) and Colombia (Cali).

3.3. *Analyzing the potentiality and probability of reinforcement corrosion in different environments*

The results are presented in Tables 5, 6 and 7 for both w/c ratio types 0.45 and 0.65. Only the data from the countries with 1 year exposure results are presented:

3.3.1. *Concrete with w/c = 0.45*

From the mechanical strength point of view, the best concrete was obtained in Colombia (>50 MPa). However, effective porosity values are in the order of 7.4% (Table 5), and capillary absorption at 0.0066 $kg\,m^{-2}\,s^{-1/2}$. These values were higher than the concrete prepared in Portugal and Chile. These parameters indicate the easiness with which aggressive agents could penetrate the concrete, so the concrete prepared in Portugal would be the one with the best quality from the durability point

Table 6
Environmental and concrete characteristics (w/c = 0.65) from selected marine sites for potential estimation of corrosion onset of steel in concrete by chloride penetration

Country (station)		Portugal (Cabo Raso)	Venezuela (La Voz)	Spain (Vigo)	Colombia (1) (Buenaventura)	Colombia (2) (Buenaventura)	Chile (Valparaiso)
Environment (yearly average)	RH (%)	77.0	90.0	69.0	89.2	89.2	82.8
	TOW fraction $f(\tau)$	0.58	0.67	0.31	0.89	0.89	0.70
	Temp. (°C)	14.1	29.35	15.9	25.9	25.9	15.3
	Cl^- ($mg\,m^{-2}\,d^{-1}$)	1215	166.52	156.21	29.0	29.0	19.26
	Rain ($mm\,year^{-1}$)	140.2	398	1267.6	6581	6581	500
w/c = 0.65							
fc_k(Mpa)/28 days		32.75	26.80	27.0	36.10	28.01	19.80
C_3A		8.39	10.72	0.40	5.73	5.45	6.6
ε (%)			15.41	7.15	12.0	12.0	16.13
m ($s\,m^{-2}$)			3.71×10^7	6.1×10^7	7.28×10^7	4.50×10^7	2.25×10^7
k ($kg\,m^{-2}\,s^{-1/2}$)		0.0077	0.025	0.0091	0.0122	0.0085	0.0341
Cement content ($kg\,m^{-3}$)		260	355.4	300	335	306	323

Table 7
Environmental and concrete characteristics (w/c = 0.65) from selected urban sites for potential estimation of corrosion onset of steel in concrete by carbonation

Country (station)		Venezuela (Maracaibo)	Spain (IETcc)	Chile (Santiago)	Portugal (Lisbon)	Colombia (Cali)
Environment (yearly average)	HR (%)	72.49	62.8	61.2	74.5	69.3
	TOW fraction $f(\tau)$	0.280	0.204	0.130	0.430	0.014
	CO_2 ($mg\,L^{-1}$)	0.920	0.910	1.740	0.706	0.600
	Rain ($mm\,year^{-1}$)	347	359	992	936	1017
w/c = 0.65						
fc_k (MPa)/28 days		26.80	27.0	19.80	32.75	36.10/28.01
Cement content ($kg\,m^{-3}$)		355	300	323	260	335/306
m ($s\,m^{-2}$)		3.71×10^7	6.10×10^7	2.25×10^7		$7.28/4.5\times10^7$
k ($kg\,m^{-2}\,s^{-1/2}$)		0.025	0.0091	0.0341	0.0077	0.0122/0.0085

of view, and the one with the least reinforcement corrosion potentiality if all the concretes prepared in the different countries were to be exposed to the same environment. The concrete with the greatest reinforcement corrosion potentiality would be the one prepared in Venezuela. Besides having the lowest compressive strength, it is also the one with the highest water-absorption coefficient ($0.0082\,kg\,m^{-2}\,s^{-1/2}$), and effective porosity index (7.6%), contrary of having a greater C_3A content. In this case, however, the effect of capillary absorption is considered more important than C_3A content.

3.3.2. Concrete with w/c = 0.65

The concrete prepared in Venezuela is the one with the highest potentiality for inducing reinforcement corrosion for w/c ratio of 0.65. Although it is not the one with the lowest compressive strength, its capillary absorption ($0.025\,kg\,m^{-2}\,s^{-1/2}$) and effective porosity (15.4%) are higher than the rest. On the other hand, the concrete prepared in Portugal is of the best quality because, even though it does not have the greatest compressive strength, it has the least capillary absorption of all.

Now, to determine reinforcement corrosion probability in the different environments under this investigation, the potentiality of the environment must be analyzed jointly with that of the prepared concrete mixtures. Therefore, the analysis will be carried out depending on whether it is a marine or urban environment.

3.3.3. Marine environment

Table 5 presents, from left to right, the order in which the reinforcement corrosion potentiality, based on ISO Standard 9223 environment aggressiveness, is greater. The order was obtained based on chloride ion content only; note that the TOW ($>\tau_3$) is similar in all marine sites presented in this work. From the results summarized in Table 5, which also shows the characterization of the different types of concrete evaluated (w/c = 0.45) in the different countries, it can be seen that, even though the Portugal concrete is of good quality, the reinforcement would have the greatest probability of corrosion in this concrete given that this environment has a high chloride-ion concentration (1215 mg m^{-2} d^{-1}).

In the cases of La Voz in Venezuela and Vigo in Spain, with similar time of wetness and chloride content in the environment, even though Venezuelan cement has a greater C_3A content (10% in comparison with 0.4% for Spain), it is the worst quality concrete because, besides having the lowest compressive strength, it has a high effective porosity (>7%) and capillary absorption (0.082 kg m^{-2} s$^{-1/2}$). Therefore, this concrete is expected to be the second in reinforcement corrosion probability, followed by the one prepared in Spain. Other environmental effect would be the average annual temperature, which in Venezuela is the highest, and undoubtedly increases chloride-ion diffusion through the concrete. Although this effect is also observed in Colombia, the chloride content in the Buenaventura atmosphere is low compared with La Voz test station; besides, in Buenaventura it rains almost all year long, which would constantly wash the chlorides from the concrete surface, thereby diminishing chloride ingress. Therefore, the greatest-to-least reinforcement corrosion probability will be: Cabo Raso/Portugal > La Voz/Venezuela > Vigo/Spain > Buenaventura/Colombia > Valparaíso/Chile. Similar effect is found for the w/c = 0.65 concrete (Table 6).

3.3.4. Urban environment

In these environments, only the probability of corrosion by carbonation will be analyzed for concrete with w/c = 0.65 (Table 7) since, as it is well known for good quality concrete, such as those prepared with w/c = 0.45 (Table 5), there is a very low potentiality and probability of reinforcement corrosion by carbonation.

Table 7 presents the average annual values of the factors that are most likely to influence CO_2 ingress into the concrete. In accordance with CO_2 content in the atmosphere, the most aggressive would be the environment at the Maracaibo airport test site in Venezuela. However, to increase CO_2 ingress into concrete, low relative humidity (< 80%) is needed. On the other hand, to have reinforcement corrosion, RH should be >80%, so the time of wetness fraction ($f(\tau)$) might be used as an important parameter to indicate carbonation-induced corrosion. For example, the Lisbon test site in Portugal is the one with the greater $f(\tau)$ value. Conversely, CO_2 content in Lisbon is low, as compared to the Venezuelan test site (Maracaibo) atmosphere, which would be the most aggressive test site by CO_2, followed by Santiago/Chile, IETcc/Spain, Lisbon/Portugal and Cali/Colombia.

Note that, even though average RH in Colombia (Table 7) is very favorable for concrete carbonation (69.3%), $f(\tau)$ value indicates that this humidity will be at values that would potentially induce reinforcement corrosion during only 1.4% of the yearly total, so this would be the least aggressive environment. When the characteristics of the concrete are evaluated (Table 7), it can be seen that Venezuela, as stated above, has the lowest quality concrete ($fc_k = 26.80$ MPa, $\varepsilon = 15.41\%$ and $k = 0.025$ kg m^{-2} s$^{-1/2}$). This means that, being the most potentially aggressive environment of the ones analyzed so far, there is a very high probability of corrosion onset at this test site by carbonation. The order of corrosion by carbonation aggressiveness (from greatest to least) would be: Airport/Venezuela > Santiago/Chile > IETcc/Spain > Lisbon/Portugal > Cali/Colombia.

4. Conclusions

The test sites and the results presented here only represent their specific microclimates. Therefore, one must be careful with extrapolating these results to avoid confusion or misunderstanding regarding reinforced concrete corrosivity. The following conclusions may be drawn from the results reported so far in the study:

- To determine the probability of reinforcement corrosion, a joint analysis of the potentiality of the exposure environment and the concrete surrounding the reinforcement must be carried out.
- In marine atmospheres, chloride content in the environment is a decisive factor when evaluating the probability of reinforcement corrosion.
- In urban atmospheres, concrete quality, CO_2 content and the TOW fraction ($f(\tau)$) are the most important factors to be considered when evaluating the probability of reinforcement corrosion.
- Preliminary results at 1 year of exposure showed clear differences among the reinforced concretes exposed to specific microclimates (in this case marine and urban).

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