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Concrete deterioration in Colombian urban atmospheres

Deterioro del concreto en ambientes urbanos de Colombia

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Abstract

The combination of atmospheric pollutants, such as carbon dioxide and chlorides has a synergistic effect accelerating the degradation process of concrete. However, in Colombia it has not been carried out field tests in real urban environments to assess the deterioration of concrete and its relation to both, carbonation and chloride content. In this work, cylindrical concrete probes were exposed in different urban atmospheres with the aim of establishing correlations between the concrete deterioration and the type of atmosphere. To evaluate the corrosion rate on the rebar and the percentage of carbonated probe, Electrochemical Impedance Spectroscopy (EIS) and physicochemical tests with phenolphthalein were used, respectively.

----- *Keywords:* Concrete, atmospheric deterioration, carbon dioxide, chlorides, EIS

Resumen

La combinación de contaminantes atmosféricos tales como el dióxido de carbono y los iones cloruro tiene un efecto sinérgico que acelera los procesos de degradación del concreto. Sin embargo, en Colombia no se han llevado a cabo estudios de campo en ambiente urbanos reales que permitan evaluar el deterioro del concreto y su relación con la carbonatación y el contenido de iones cloruro. En este trabajo, probetas cilíndricas de concreto fueron expuestas en diferentes atmósferas urbanas con el ánimo de establecer correlaciones entre el deterioro y el tipo de atmósferas. Para evaluar la velocidad de corrosión

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de la barra de refuerzo y el porcentaje de carbonatación de la probeta se empleó la Espectroscopía de Impedancia Electroquímica (EIS) y ensayos fisicoquímicos con fenolftaleína, respectivamente.

----- *Palabras clave:* Concreto, deterioro atmosférico, dióxido de carbono, cloruros, EIS

Introduction

Rebar protection provide by the concrete is improved by high pH values reached after the hydration reactions. In this alkaline environment, the steel is normally protected from corrosion by the formation of a passive oxide film which acts as a barrier to the anodic dissolution of the metal [1, 2]. However, the passivity breakdown occurred when the structure interacts with the atmosphere [3]. Steel rebar can be contaminated by chloride ions from sea spray or windblown salt. This fact leads to the formation of corrosion products on their surface [4]. The presence of the corrosion products affects the bond strength between steel and concrete [4, 5]. Another aggressive agent for the concrete structures is the atmospheric carbon dioxide which reacts with the humidity and produces species with lower pH values such as calcium hydroxide. This phenomenon is known as carbonation. The carbonation of concrete reduces the initially high pH value of the pore solution phase to a level at which the passive film can breakdown, allowing the steel to corrode [5-7]. The combination of these agents has a synergistic effect accelerating the degradation process [8]. No studies have been carried out in Colombia in real urban environments to assess the concrete deterioration and its relationship to carbonation and chloride content.

The research described in this paper includes electrochemical and physicochemical tests to evaluate the impact of aggressive agents, such as atmospheric carbon dioxide and chloride ions on mortar specimens. The aim of the present work is to look for correlations between the concrete deterioration and the type of atmospheres after exposures in different Colombian urban sites. For this end, cylindrical reinforced and non-reinforced probes were built and exposed to different urban atmospheres. To evaluate the corrosion rate on the rebar and the percentage of carbonated probe, Electrochemical Impedance Spectroscopy (EIS) and physicochemical test with phenolphthalein were used, respectively.

Methodology

Field tests were performed in three cities with different characteristics (altitude over sea level, distance to the coast and population). Table 1 shows the main characteristics of these cities. Three monitoring stations were placed in each city for the concrete exposures. The cites were classified in terms of its economical activity (industrial, commercial or residential). A total of nine urban monitoring stations were used.

Table 1 Characteristics of the cities selected for field test

City	*Altitude (m)*	*Longitude*	*Latitude*	*Distance from the coast (Km)*	*Population*
Barranquilla	2	74º 47’ 20”	10º 59’ 16”	10	1.386.865
Medellín	1.479	75° 34´ 05”	6° 13´ 55”	210	2.249.073
Bogotá	2.630	74°04’51”	4° 35’56”	360	6.778.691

On each station, 7 probes were installed as follows: 4 reinforced and 3 non-reinforced, for a total of 63 mortar probes (27 non-reinforced and 36 reinforced) with dimension of 5 inches on length and 2 inches on diameter. Type I cement Portland, standard sand with granulometry according to ASTM C778 [9], water and structural steel according to ASTM 706 [10] with 1.5 cm of diameter were used to build the probes.

For the reinforced probes, the rebar was cut into 14 cm sections. Besides, both ends of the rebar and the mortar-rebar-air interface were covered with a mastic-epoxy system to reduce or eliminate the anodic spots, leaving a free surface of about 40 cm^2. Water/cement ratio of 0.6 and sand/cement ratio of 3 were used to fabricate the mortar specimens. Figure 1 shows the configuration and dimensions of the mortar probes. Thereafter, the rebars were positioned vertically at the center of the moulds, where the mortar were cast and stored at ambient conditions in the laboratory for 24 h. After being dismolded, the specimens were placed in a curing room (RH > 80%, T = 22 ± 1 °C) for a month. At the end of the curing period, the probes were evaluated on the different urban environments every 4 months, during one year.

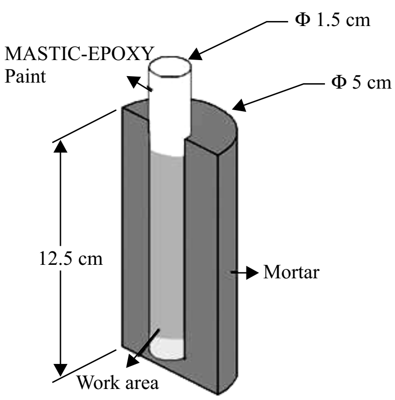

Figure 1 Diagram of mortar probes

A BAS-ZAHNER IM6e potentiostat/galvanostat, saturated calomel electrode (SCE) as reference electrode, deionized water as electrolyte and platinum wire as counter electrode were used to take EIS measurements. Before each measurement, the probes were kept inside the electrolyte during 30 minutes to stabilize the potential and then scanning frequency measurements between 10 mHZ to 100 KHz were performed. For open circuit potential measurements, a SCE having a wetted cotton tip was placed over the concrete surface and the potential was periodically measured between the rebar and the reference electrode using a FLUKE high impedance multimeter. Finally, to determine the area of carbonation, 3 cm sections were cut and a phenolphthalein solution was poured on the surface.

Results and discussion

Figure 2 shows the average area of carbonation (in percentage) for the specimens on each urban station after 4, 8, and 12 months. Measurements of the carbonation profile varied as follows: 31 – 40 % for the first 4 months, 38 – 62 % after 8 months and 44 – 62 % after 12 months.

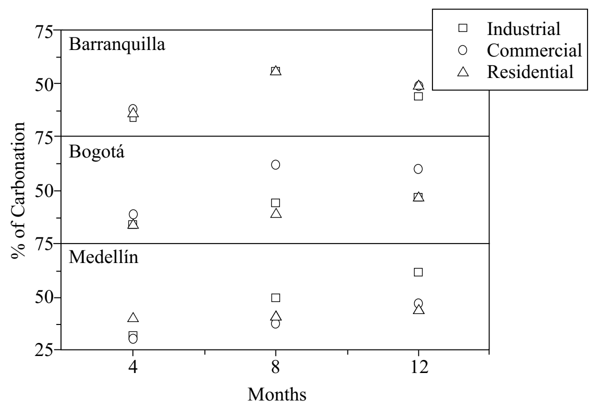

Figure 2 Percentage of carbonation on each urban station after 4, 8, and 12 months exposure

In Barranquilla, the progress of the carbonation was similar for each station. It was higher between 0 and 4 months and then levels off. According with these results, Barranquilla station showed a similar aggressiveness behavior for the mortar probes.

The results in all Bogotá stations showed an increasing carbonation progress. The behavior was similar in both, residential and industrial station. Commercial site showed greater carbonation because this area has a very high CO_2 concentration probably due to a heavy vehicular traffic.

In the case of Medellín, the behavior was different for each station. In the last two periods, the progress of carbonation in industrial stations was clearly higher than in the other two stations.

Carbonation phenomenon could changes the properties of concrete, specifically the mechanical and electrical resistance. As the carbonation progresses, hydroxides in solution (calcium, sodium and potassium) present in the pores of the mortar are converted into solid non-soluble carbonates. These carbonates fill the pores, decreasing the mortar porosity. The lower porosity causes a rise of mortar density, which improves some properties such as compressive strength, hardness and elastic yield. However, the rise of the mortar density may have a negative effect because of the ductility and the adhesion between rebar and mortar decreases. On the other hand, carbonation reduces the charge transport capacity by reducing the concentration of ions available for that purpose. In the same way, lower mortar porosity produces an increase on the mortar resistivity; because there is a reduction in sites where charge can be transported [6, 11, 12].

EIS tests were carried out to determine the rebar behavior in mortar. Figure 3 shows the Nyquist diagram obtained during the curing period for a reinforced probe. A similar geometry was observed in each plot, a capacitive arc at high frequencies and linear behavior at low frequencies. In addition, there was an increase in the capacitive arc with time of curing. In this case, the arc at high frequencies, describes the behavior of mortar (pore solution resistance and mortar resistance) and its increase with curing time. These may be attributed to micro-structural change (mortar hardening and a rise in mechanical strength) due to mortar hydration, according with Koleva *et al* [13]. On the other way, at low frequencies, Nyquist plot shows a linear behavior. This behavior results from the diffusion of oxygen through the mortar towards the steel/mortar interface because the diffusion process is the controlling process in this situation [14].

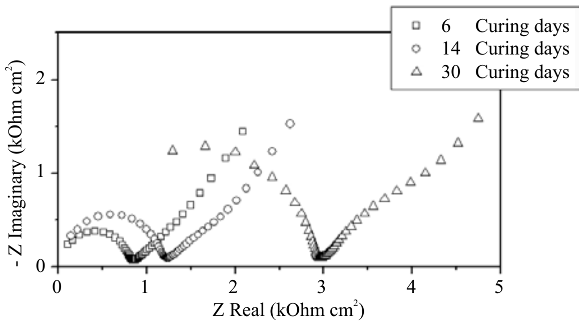

Figure 3 Nyquist diagrams obtained during curing period for a reinforced probe

Figure 4 shows the concrete pore resistance values (capacitive arc diameter at high frequencies) taken from Nyquist diagrams and its trend with exposure time. It is noted that the pore resistance values measured tend to increase with increasing exposure time. Diminution of the mortar density and loss of the charge transport capacity, increase the mortar resistance (pore solution resistance and mortar resistance) due to carbonation progress, as explained above.

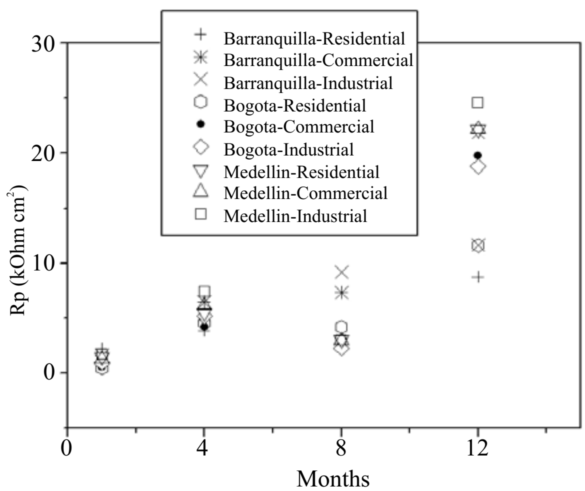

Figure 4 Reinforced concrete pore resistance vs. Exposure time for each urban area

Table 2 shows the polarization resistance values (Rp) taken from the last period and the corrosion rate (I_{corr}) determined by the Stern-Gary [15] equation for each station.

Table 2 Polarization resistance and corrosion rate for the last period on each urban place

Station	*Rp* *(Ohm. cm²)*	I_{corr} *(mA/cm²)*	*Corrosion level [15]*
Barranquilla			
Industrial	55.0 x 10^3	0.473	Moderate
Commercial	56.5 x 10^3	0.460	Moderate
Residential	27.9 x 10^3	0.932	High
Bogotá			
Industrial	30.4 x 10^3	0.855	High
Commercial	27.9 x 10^3	0.932	High
Residential	29.4 x 10^3	0.884	High
Medellin			
Industrial	46.0 x 10^3	0.565	High
Commercial	49.5 x 10^3	0.525	High
Residential	52.8 x 10^3	0.492	Moderate

Table 3 presents the average chloride concentration measured in the 9 stations during the same year [16]. In the residential station of Barranquilla, placed near to the seashore, a high chloride concentration was measured, which means a high aggressiveness environment. In this case, both the carbonation progress as well as the high chloride concentration may cause breakage of the steel passive layer, which could explain the elevate corrosion rate obtained through EIS. According to Table 3, in Bogota city, all the sites showed a similar corrosion level, exhibiting a corrosion rate slightly higher at the commercial station. This is in agreement with the results obtained in carbonation test, where the station had the highest percentage of carbonation progress. In this case, the rebar deterioration was due to mortar carbonation because the concentration of chloride was below 2 mg/m².day, corresponding to atmospheres with low chlorides concentration, according to ISO classification [17].

Table 3 Average chloride concentration for one year of exposure

Station	Cl^- *(mg/m²d)*
Barranquilla	
Industrial	43.35
Commercial	26.49
Residential	96.59
Bogotá	
Industrial	1.42
Commercial	1.32
Residential	1.22
Medellin	
Industrial	2.12
Commercial	1.03
Residential	1.61

The results obtained for Medellín city show high corrosion levels for commercial and industrial stations. For residential area, the level is moderate. Deterioration of rebar in Medellín stations was due mostly to carbonation process because the concentration of chloride was very low.

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Conclusions

The highest corrosion rate were presented in residential station of Barranquilla, which contained high concentration of chloride ions in the air, and in all Bogotá stations, where the main source of deterioration of the rebar was the carbonation of mortar.

The impedance curves showed a capacitive loop associated to mortar behavior (resistance of the pore solution and resistance of mortar) during curing. The increase of the impedance with time could be attributed to micro-structural changes due to mortar hydration. Also, low frequencies tails were noted, which were associated with double layer phenomena on the rebar surface.

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