Airborne salinity penetration in the coastal tropical climate of the Havana Cuba

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Palabras clave: Concreto, medio ambiente, corrosión, durabilidad.
Key words: Concrete, environment, corrosion, durability.

RESUMEN. Se estudió la penetración de la salinidad atmosférica en el clima tropical costero de La Habana, donde las estructuras constituyen un obstáculo para la entrada y penetración del aerosol marino. La deposición de iones cloruro fue medida en sitios de exposición ubicados a diferentes distancias desde el mar. La deposición de las partículas de iones cloruro de mayores pesos y tamaños alcanzó un mínimo a una distancia del mar de alrededor de 32 m. La velocidad promedio anual del flujo de viento demostró una mayor influencia sobre la corrosividad de la atmósfera en el sitio más cercano al mar sin la presencia de obstáculos. La velocidad del flujo de viento no solo fue la variable meteorológica que influyó en la deposición de iones cloruros, sino también, el complejo humedad-relativa-temperatura. La influencia de este complejo fue mayor en el sitio más cercano al mar. Una disminución de la temperatura del aire debido a fenómenos meteorológicos transitorios como la entrada de los frentes fríos, fue el factor climático que más influyó en la mayor deposición de iones cloruros en la ciudad.

ABSTRACT. Penetration of airborne salinity in a tropical coastal in Havana City where building structures constitute obstacles for entrance and distribution of the marine aerosol was studied. Chloride ions deposition in exposure site at different distances from the sea was measured. In Havana City, at a distance from the sea about 32 m, deposition of heavier and big chloride particles reaches a minimum. Average annual wind speed flow showed a higher influence on atmospheric corrosivity in the site close to the sea and without obstacles to the wind flow. Wind speed flow is not the only meteorological variable influencing on chloride ions deposition, but also temperature-humidity complex. The influence of this complex is higher in the site close to the seashore. A decrease in air temperature, due to transitory meteorological phenomena, such as the entrance of cold fronts, is the climatic factor with higher influence in chloride ions deposition in the City.

INTRODUCCIÓN
Changes in the chloride deposition rate versus distance from the sea, as an indicator of the airborne salinity penetrations, has been determined in several coastal areas of different countries, but generally in flat territories, not in cities. In a coastal city like Havana, at short distances from the sea, building structures and natural vegetation of high altitude may cause a significant screening effect. As it is well known, chloride deposition is the main aggressive agent in the initiation and propagation of the phenomenon of atmospheric corrosion in reinforced concrete and carbon steel building structures. Wet candle has been the device more frequently used to determine chloride deposition.
Airborne salinity penetration studies were started in Cuba in 1979 at different flat coastal territories. However, its behavior respecting distance from the sea in Cuban cities was not studied. The device used for chloride deposition evaluation was Dry plate.\textsuperscript{3-8} Statistical models have been used to study the behavior of chloride deposition respecting distance from the sea in coastal areas.\textsuperscript{9-11} A linear decreasing function was not useful to represent this behavior, but a bilogarithmic decreasing linear function ($D = aX^{-b}$) or an exponential decreasing function ($D = ae^{(-b)X}$) have been recommended. $D =$ Chloride deposition (mg m$^{-2}$ day$^{-1}$), $X =$ Distance from the sea (m), $a$ and $b =$ Regression coefficients. A comparison between bilogarithmic and exponential models applied to a coastal city to study penetration and distribution of airborne salinity from chloride deposition determination has not been reported previously.

Formation, transportation and deposition of airborne salinity strongly depend on wind speed flow. When wind speed flow increases, heavier salt particles can reach longer distances from the sea in case of a flat territory. However, there is no consensus about the threshold of annual wind speed flow necessary to increase chloride ions concentration in the air in coastal zones in flat territories. Using the model $C = ae^{bv}$, where $C =$ Chloride concentration (µg m$^{-3}$), $v =$ Annual average wind speed flow (m s$^{-1}$), $a$ and $b =$ Regression coefficients, a criteria is established to correlate chloride concentration and annual wind speed flow. This model was used in studies carried out in others coastal zones, but in this case determining deposition and not chloride concentration.

The equivalent model is $D = ae^{bv}$ where $D =$ Chloride deposition (mg m$^{-2}$ day$^{-1}$). Good data fitness was obtained. The results also showed there is no consensus about wind speed flow threshold necessary to increase chloride deposition in coastal zones in flat territories.\textsuperscript{12-14} The influence of wind speed flow on the increase of chloride concentration or chloride deposition has been studied, in general, only at specific distances from the sea in flat territories and open atmospheres.

Regarding to other factors influencing in the chloride depositions, it was proposed that, when the salt particles are generated, they rapidly become equilibrated with the environment in the marine aerosol and depending on temperature and relative humidity condition; they can turn into solutions saline or salt crystals.\textsuperscript{15} Exactly if the relative humidity is found higher 70 %, aerosol particles are deposited as saline solutions and not as crystals. It may increase atmospheric corrosivity. Chloride salts hygroscopicity increases particles size and promotes their deposition.

On the other hands, it was illustrated that the influence of relative humidity on salt concentration is particularly important between 50 and 70 % due to salt wetting.\textsuperscript{16} The authors also observed the washout effect due to rainfall, is more effective at higher relative humidity levels. It is concluded that the salinity wetting increase the salt particles sizes, as well as, rainfall remove a great amount of salt aerosol.

The influence of the air temperature decreasing due to entry of cold fronts on salt particle chloride depositions increasing has not been taken into account.

The ISO 9223: Second edition 2012-02-01 standard establishes: “The airborne salinity, based on chloride deposition, is strongly dependent on the variables influencing the transport inland of sea-salt, such as wind direction flow, wind speed flow, local topography, distance of the exposure site from the sea”.\textsuperscript{17} This standard neither considers the influence of air temperature decreasing in airborne salinity penetration.

**EXPERIMENTAL PART**

**Selection and installation of the exposure sites**

Seven exposure sites (S) at different distances from the sea in Havana City Cuba, were selected (S1-20 m, S2-170 m, S3-600 m, S4-1 365 m, S5-1 772 m, S6-2 364 m and S7-4 911 m). Only exposure site Number 1 (S1-20 m), was located in the open atmosphere in front to the sea (Fig.1). Distances from the sea in north direction from the exposure site to the shoreline was measured using Google Map software.

On each exposure site, a wooden rack with two dry plate devices was placed. The dry plate device is an absorbent cloth used to determine the chloride deposition during the period of measurement. The wooden rack oriented toward the sea, was located inside an open shed with water gabled at a height over 3 m to the ground, protected from the rain to avoid the washing effect.

**Chloride deposition determination**

Chloride deposition ($D$) was determined based on Cuban standard through Dry plate method. Dry plate device consisted in a piece of absorbent cloth sizing 320 mm x 220 mm located at 45 degrees to the horizontal and in front to the north direction (sea).\textsuperscript{18} Two pieces of cloth, perfectly cleaned and washed with distilled water were used for every site. Clothes were exposed monthly during one year. Chloride deposited on the clothes was determined by chemical analysis. After retired, clothes were kept into plastic bags up to chemical analysis. Two data of chloride deposition (mg m$^{-2}$ day$^{-1}$) for every month of exposure (in the period October/2007-september/2008) were obtained: one for device 1 ($D_1$) and other for device 2 ($D_2$) for every exposure site (total of 24 data of chloride deposition during the year). The principle of this method is the same than Dry plate described on ISO: 9225:2012.\textsuperscript{19} The monthly chloride deposition and average annual values were plotted with respect to distance from the sea.
Relative humidity, air temperature, wind speed flow and wind speed flow direction
Relative humidity (%), air temperature (°C), wind speed flow (m s\(^{-1}\)) and wind speed flow direction data were obtained from the main meteorological station of the Cuban Institute of Meteorology in Havana City, selected as exposure site number 4 of the present research (Fig. 1). Average monthly values for the year of evaluation were processed (October/07 to September/08). Wind speed flow values processed corresponded to east-northeast to west-northwest directions (wind speed flow coming from the sea).

RESULTS AND DISCUSSION
Chloride deposition at different distances from the sea
Significant differences in chloride deposition depending on the climatic season were found. Higher values are usually reported in winter (dry) period, that is to say, since October up to April (Fig. 2 a), (b), (c), (d)). Chloride deposition data was divided in two sets, according to the two main climatic seasons in Cuba, dry period-winter (Oct-Apr) and wet period-summer (May-Sept). It is important to note that deposition values in exposure sites 2 to 7 remained almost constant in dry period (Fig. 2 a) and (c)). At these six exposure sites the influence of building construction and groves constitutes an obstacle for wind flow. Small changes are observed in summer period (Fig. 2 b) and (d)) particularly in the exposure site located at about 1 365 m from the sea corresponding to site number 4 (S4-1 365 m). As can be seen in the map (Fig. 1), this site is located close to the entrance of Havana Bay. At this position, there is not only influence of the open sea, but also of Havana Bay. This condition explains why higher changes in chloride deposition are reported for this site.

The highest chloride deposition was recorded at the site located at 20 m from the shoreline, the site very close to the sea. At this site there are no obstacles to the wind flow. Higher values of chloride deposition were reported during the months having lower average temperature (November-March).

Data reported from the Institute of Meteorology showed the arrival of 17 cold fronts to Havana City during the year of the research. Seven cold fronts were classified as moderate intense because maximum wind speed flow determined was over 9 m s\(^{-1}\). The rest of the cold fronts were classified as low intense. These seven moderate cold fronts arrived in the period November-March (dry period).

A linear relationship between chloride deposition data determined using dry plate method and wet candle method is established in ISO 9225:2012. Annual average chloride deposition data for every dry plate device exposed at 20 m to the shoreline was 760.05 and 778.81 mg m\(^{-2}\)day\(^{-1}\), respectively. Converting these values to wet candle gives an estimate of 1 824.12 mg m\(^{-2}\)day\(^{-1}\) and 1 869.14mg m\(^{-2}\)d\(^{-1}\) for a total average of 1 846.63 mg m\(^{-2}\)d\(^{-1}\). Annual average chloride deposition is over the range 300 < S < 1 500, maximum established in ISO 9225:2012 standard. Extreme corrosion aggressivity is expected based on chloride deposition. A significant deterioration of reinforced concrete and metallic structures very close to the sea in the open atmosphere is observed in the City. It is a consequence of extreme corrosion aggressivity caused by a very high chloride deposition in places located in front to the open sea.\(^{20, 21}\)
Reports from a coastal zone at the east of Brazil in the north coast of Sweden, and the shoreline of South Korea proposed two statistical models to explain changes in chloride deposition versus distance from the sea: an exponential decreasing function and a bilogarithmic decreasing function. The statistical models were fitted using data corresponding to average chloride deposition at exposure times of 6, 12 and 18 months respectively.

For data of average annual chloride deposition in each exposure site in Havana City, a better fitness is obtained in the model corresponding to an exponential decreasing function (Fig. 3 a), b)) in comparison with the model corresponding to a bilogarithmic decreasing function (Fig. 3 c), d)).

A considerable decrease in chloride deposition can be observed at a short distance from the sea (see difference in chloride deposition between sites S1 and S2, the last one located at 170 m to the sea (Fig. 3 a), b)). It can be explained under the supposal that deposition of heavier and higher saline particles coming from the ocean and the area of breaking waves reaches only a distance lower than 170 m from the sea.

Big chloride nuclei formed in the ocean and in the breaking waves reach up to a given distance from the sea. After this distance, chloride deposition continuously decreases. This area at less than 170 m can be considered as coastal atmosphere. After this distance, only small chloride aerosol particles coming from the ocean continue penetrating in the land. The model based on a decreasing exponential function can be used to explain this behavior. Distance from the sea where decrease of chloride deposition is stopped is obtained from coefficient "b" corresponding to exponential decreasing function, that is, distance from the sea where the atmosphere can be defined as coastal. This aspect has not been reported previously.

**Fig. 2.** Chloride deposition determined at different distances from the sea during dry period (October-April) a) and c) and wet period (May-September) b) and d).
Fig. 3. Data fitness for the two statistical models proposed for the relation between average annual chloride depositions versus distance from the sea.

According to the mathematical conditions of the model corresponding to an exponential decreasing function, it is possible to define the parameter \( t = \frac{1}{b} \) considered as the distance to the shoreline where decreasing rate of chloride deposition stops. The equation transforms into \( D = a e^{-x/t} \). Based on this supposal of the model, the estimated distance is about 32 m. The distance obtained can be used to establish two levels of atmospheric corrosivity for reinforced concrete and construction materials. At distances longer than 32 m, aerosol particles depositing is those coming from the Ocean having small size and weight. Starting from this distance, atmospheric corrosivity can be classified in other level.

For Cuba and Spain, reports corresponding to flat territories and open coastal atmospheres, establish longer distance to the shoreline where marine aerosol having big particles can reach: 150-250 m. No statistical fitness to a model was carried out.

Climatic factors influencing in chloride deposition

Wind speed flow

Chloride deposition in the seven exposure sites increased when annual average wind speed flow coming from the sea increases corresponding to east-north-east and west-north-west directions (Fig. 4 a), b), c) y d).

A tendency to increase chloride deposition starting on annual average wind speed flow of about 3 m s\(^{-1}\) is observed. These results are in agreement with other reports from Australian coasts, Mediterranean coasts at Tarragona, Spain and at the east coast of Brazil, city of Joao Pessoa without screening by building structures and grove. Different threshold values of wind speed flow are reported in the coast of the North Sea in Sweden and for Glacial Arctic and Pacific Ocean in Russia; in the open atmosphere, without obstacles, the necessary wind speed flow to observe an increase in chloride deposition was 5 and 6 m s\(^{-1}\) respectively. However, in the city of Chittagong, Bangladesh, in presence of screening conditions by building structures (located in the Indian Ocean coast), the annual average wind speed flow at which the chloride deposition increased, determined by the wet candle method, was 5.5 m s\(^{-1}\). The study was based on the evaluation of the effectiveness of protective mortar designed to resist penetration of sea salt, in order to increase the
durability and service life of the structures directly exposed to the action of chloride. The results show there is no consensus on the wind flow speed threshold to increase the chlorides deposition.

![Graphs showing chloride deposition vs wind speed](image)

**Fig. 4.** Behavior of chloride deposition depending on annual average wind speed flow coming from the sea.

**Behavior of relative humidity and air temperature**

Monthly average relative humidity (RH) and air temperature (T) data during the test period was lower in the dry season (winter period), excepting the month of October (Fig. 5). The month of October is included in the wet season in Cuba (May-September), at these months, due to abundant and heavy rain; the highest monthly average relative humidity is recorded.

Monthly average relative humidity is always over 70%. At this level of humidity, chloride deposition occurs mainly as saline solution and not as crystals. Under these conditions, a very corrosive atmosphere is originated, not only for reinforced concrete structures, but also for every metallic material exposed to the atmosphere. Average monthly wind speed flow (WS) measured was higher in the dry period (winter) respecting wet period (summer). It could be one of the reasons why higher chloride deposition is determined in the dry season (winter period).

![Graph showing changes in RH, T, and WS](image)

**Fig. 5.** Changes in relative humidity, air temperature and wind speed flow during the test period (one year). Dry season: October-April. Wet season: May-September.
The influence of relative humidity-temperature complex and wind speed flow in monthly chloride deposition for every dry plate device is observed through statistical regressions (Table 1).

Multiple statistical regressions obtained show the dependence between chloride deposition versus temperature, relative humidity and wind speed flow. The best fitness is obtained for the exposure site located at 20 m from the sea. According to the regression coefficients obtained and their sign (+ or -), a different influence of relative humidity and temperature is observed for the exposure sites at 20 m and 600 m from the sea, that is, two of the exposure sites where a small extent of screening is observed, particularly respecting building structures.

**Table 1.** Multiple statistical regressions showing the relation between chloride deposition and meteorological parameters for seven exposure sites.

<table>
<thead>
<tr>
<th>Exposure Sites</th>
<th>R² (%)</th>
<th>P</th>
<th>Regression</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1-20 m</td>
<td>91</td>
<td>0.0000</td>
<td>$DCl_1^- = 8.728.86 + 27.73RH + 410.72T + 88.55WS$</td>
</tr>
<tr>
<td>S2-170 m</td>
<td>90</td>
<td>0.0000</td>
<td>$DCl_2^- = 8.603.76 + 23.63RH + 124.73T + 103.02WS$</td>
</tr>
<tr>
<td>S3-600 m</td>
<td>73</td>
<td>0.0101</td>
<td>$DCl_1^- = 59.28 + 0.36RH - 2.93T - 2.22WS$</td>
</tr>
<tr>
<td>S4-1 365 m</td>
<td>73</td>
<td>0.0111</td>
<td>$DCl_2^- = 60.67 + 0.36RH - 2.96T - 2.40WS$</td>
</tr>
<tr>
<td>S5-1 772 m</td>
<td>63</td>
<td>0.0351</td>
<td>$DCl_1^- = 0.42 + 0.28RH - 0.97T + 2.10WS$</td>
</tr>
<tr>
<td>S6-2 365 m</td>
<td>66</td>
<td>0.0320</td>
<td>$DCl_2^- = 0.56 + 0.22RH - 0.88T + 1.96WS$</td>
</tr>
<tr>
<td>S7-4 911 m</td>
<td>75</td>
<td>0.0077</td>
<td>$DCl_1^- = 207.40 + 1.45RH - 10.19T - 1.30WS$</td>
</tr>
<tr>
<td>S7-4 911 m</td>
<td>76</td>
<td>0.0060</td>
<td>$DCl_2^- = 212.79 + 1.47RH - 9.09T - 0.88WS$</td>
</tr>
<tr>
<td>S7-4 911 m</td>
<td>74</td>
<td>0.0093</td>
<td>$DCl_1^- = 21.01 + 0.12RH - 0.95T - 1.02WS$</td>
</tr>
<tr>
<td>S7-4 911 m</td>
<td>74</td>
<td>0.0093</td>
<td>$DCl_2^- = 11.44 + 0.12RH - 0.69T - 0.42WS$</td>
</tr>
</tbody>
</table>
Regression equations obtained for sites located 20 and 600 m from the sea show an increase in chloride deposition when wind speed flow increases if relative humidity and temperature remain constant. In the other sites, chloride deposition decreases when wind speed flow increases if temperature and relative humidity remain constant. A clear difference in the influence of wind speed flow is determined. In the site located in front to the sea, wind speed flow can bring chloride aerosol directly from the sea.

The same situation could occur in the site located at 600 m. Perhaps the wind flow reaching the other five sites is coming not directly from the sea and when wind speed flow increases marine aerosol is dispersed. For both exposure sites (S1-20 m and S2-600 m), it appears that the chloride deposition as saline solution is not only dependent on an increase in wind speed flow, but an increase in the relative humidity and a decrease in temperature. For the rest of the exposure sites, when relative humidity increases and temperature decreases, the chloride deposition as saline solution can occur due to a decrease in wind speed flow. At these sites, only small particles of chloride aerosol are present.

For all regression equations obtained, chloride deposition increases when relative humidity increases. Chloride deposition as saline solution may occur when $RH > 70\%$. In the case of temperature, a decrease in temperature causes an increase in chloride deposition. It is very well known that normally, relative humidity increases when temperature decreases, so the influence of temperature-humidity complex in chloride deposition is very clear. In a report about an experiment performed in a coastal region in the south of France, it was determined an increase in chloride deposition when average wind speed flow decreases (the influence of the temperature-humidity complex was not considered). Deposited chloride particles ranged in size between 0.045 and 0.3 µm. Exposure sites were located at long distances to the sea. Perhaps, under quite turbulent wind regimes, characteristics of a City like Havana, chloride deposition as saline solution may increase when wind speed flow decreases, taking into account the existence of relative humidity over 70 %.

The regression coefficients affecting temperature show higher values (Table 1). It shows temperature is a very significant parameter in statistical fitness. A linear regression between chloride deposition and temperature show a good statistical significance (Fig.6. a), b), c) d)). It is observed in all sites that a decrease in monthly average temperature causes a significant increase in chloride deposition, as saline solution. The same occurs in the exposure site located from 170 m from the sea, but in this case taking the annual average deposition for each device. The best fitness is obtained for the exposure site located 20 m from the sea.

The linear fitness shows the higher deposition of chloride as saline solution occurs at temperature lower than 25°C, corresponding to the winter season, the period where occurs the entrance of frontal systems, their influence is more significant in the exposure site located 20 m from the sea. Therefore, the temperature decrease due to occurrence of transitory meteorological phenomena such as the entrance of cold fronts is a significant factor in chloride deposition.

![Fig. 6. Linear fitness chloride deposition versus average air temperature a) and b) exposure site located 20m from the sea, e) and f) exposure site located from a distance of 170 m from the sea.](image)
CONCLUSIONS
In Havana City, at a distance to the shoreline about 32 m, deposition of heavier and big chloride particles reaches a minimum. Data was fitted to a decreasing exponential function established between chloride deposition and distance from the sea. Extreme corrosion aggressivity is predicted for the site located in the open atmosphere in front to the sea. Average annual wind speed flow showed a higher influence on atmospheric corrosivity in the site close to the sea and without obstacles to the wind flow. Threshold value of average annual wind speed flow for increasing chloride deposition at different distances to the seashore in Havana is about 3 m s⁻¹. Based on the behavior of temperature-humidity complex, it can be proposed that chloride deposition in the City occurs more probably as drops of saline solution and not as crystallized particles at a temperature of 25°C or lower. Wind speed flow is not the only meteorological variable influencing on chloride deposition, but also temperature-humidity complex. The influence of this complex is higher in the site close to the seashore without presence of obstacles to the wind flow. A decrease in air temperature, due to transitory meteorological phenomena, such as the entrance of cold fronts, is the climatic factor with higher influence in chloride deposition in the City. Its significance is higher in the exposure site close to the shoreline (S1-20 m).

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