Construction and Building Materials 44 (2013) 452–457

Contents lists available at SciVerse ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Reinforced concrete in marine environment: Effect of wetting and drying cycles, height and positioning in relation to the sea shore

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HIGHLIGHTS

- Inspection procedure of concrete structures exposed to a marine environment.
- There is a strong effect of the wetting and drying cycles on the chloride-ion content was verified.
- Helping to understand the work in service of real reinforced concrete structures.
- Chloride ion contents were observed to have a tendency to decrease at higher places.

ARTICLE INFO

Article history:
Received 16 November 2011
Received in revised form 14 January 2013
Accepted 26 February 2013

Keywords:
Chloride ions
Corrosion
Inspection
Reinforced concrete
Salt-spray zone

ABSTRACT

Many studies about service life predictions of reinforced concrete structures are under development worldwide. However, much more advanced knowledge in this area is still needed before attaining realistic models. Real case studies are extremely important to indicate the factors of influence to be considered as variables in these models, making them closer to reality. This study of a reinforced concrete structure exposed to the environment for about 40 years is inserted in this context.

The chloride-ion contents from pillars of a reinforced concrete structure located in a marine environment, approximately 700 m away from the coastline are analyzed, showing the effect of the height (with samples from different levels), wetting and drying cycles and the positioning of the pillars in relation to the coastline.

The results show that the higher the concrete is, the lower the chloride contamination degree. It is shown that in the absence of wetting and drying cycles, the chloride-ion contents are smaller than the threshold limit of 0.40% per cement mass. Furthermore, the results show that there is no influence of the position of the pillars in relation to the sea and that the concrete located in regions where there are wetting and drying cycles is more contaminated by chloride.

1. Introduction

One of the main degradation agents of steel reinforced concrete is chloride ion, which exists in marine environments and in the production process of some industries. One of the main mechanisms that govern the chloride penetration in a steel reinforced concrete structure is the diffusion, which is the transport stimulated by a difference in concentration of the species considered [1–4].

The presence of chloride-ions above certain values in concrete structures, next to the steel reinforcement, promotes the loss of its passivity, thus causing the beginning of the corrosion process. These ions can be incorporated into concrete in its fresh-state, using chloride-based accelerating admixtures and by water or contaminated sand. In the hardened-state, contamination happens by chloride-ions entering from the outside, mainly in marine environments and by the use of deicing salts.

According to Guimarães et al. [5], the service-life models of concrete structures in marine environments consider only the micro-climates of the submersed, splash and salt-spray zones. In the latter, they do not consider that the intensity of the attack varies with the distance from the coastline. Some researches have shown that the salt-spray zone has different contamination levels as a function of the distance from the coastline, this factor normally not being considered in building codes [6–8]. Castro et al. [9] showed a large reduction of chloride-ion ingress intensity using concrete specimens exposed in a salt-spray zone, varying the distance from the coastline from 50 m to 780 m. Costa [10] also showed a large reduction in chloride-ion ingress when varying

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http://dx.doi.org/10.1016/j.conbuildmat.2013.02.078

the location of mortar specimens from 72 m to 532 m from the coastline after 5 months of exposure. Meira et al. [11] studied the chloride deposition on the wet candle at 10, 100, 200, 500 and 1100 m away from the coastline, and showed a clear decrease of airborne salinity in the first meters away from the sea with a stronger decrease in the first 200 m of distance from the sea.

Guimarães et al. [5] studied two structures over 20 years old, a beam at a harbour located next to the coast and a tower 2200 m away from the coastline, showing that the tower structure had a much lower contamination level, thus indicating that even when both of the structures were located in a marine environment, the intensity of the attack was very different between the two existing micro-climates. These facts stress the importance of considering this effect in reinforced concrete service life predictions.

However, there are others factors to be considered to predict the service life in marine structures, such as wind direction and speed, incidence of wetting and drying cycles, insolation condition, regional rainfall rate, relative humidity and exposition height, focus of this work.

It is very difficult to develop a reliable model to predict the service life of a building. However, some authors tried to predict concrete service life time based on chloride ion penetration [12–16], others concentrated their efforts trying to model the time for the occurrence of the first concrete crack of 0.1 mm by corrosion [17,18] and others yet tried more complex predictions involving service life prediction based on two effects (chloride penetration and biodeterioration) [19]. The fact is that the current prediction models are still poor with unsatisfying results.

Currently, there are many models developed in this area; however, their validation still needs to be studied and disseminated.

Therefore, it is important to study real structures. Real cases are still at a learning phase and models are being developed and adjusted to make service life predictions. This work is inserted in this context, disseminating data obtained from on-site inspection of a reinforced concrete structure that was weather-exposed to a marine environment for years.

The chloride ion contents from pillars of a reinforced concrete structure situated in a marine environment, approximately 700 m away from the coastline are analyzed here, showing the effect of height (with samples from different levels), wetting and drying cycles and the positioning of the pillars in relation to the coastline, contributing to the development and improvement of service-life models.

2. Procedure development

2.1. Structure overview

The inspected building was designed by architect Oscar Niemayer and it is located in Rio de Janeiro, Brazil. The inspection work aimed to supply data to a diagnostic, prognostic and design for repairing the reinforced concrete structure.

The structure is a 40-stories building, with two underground levels, the ground level and 37 upper levels. It is composed by a rigid core in its centre and thirteen pillars, which can be seen in Fig. 1. It was built in the early 1970s, and abandoned until nowadays, totally exposed to the weather and without any kind of protective coatings or preventive measures regarding the service-life and durability of the building.

This inspection of the structure produced important data about a real building submitted to natural aging. It can be compared to a specimen left in the environment for decades and with the possibility to be studied today. However, a study like this has some difficulties that are inherent to a real structure. Unlike a laboratory study involving specimens molded to a particular study, in this case, there are many unknown variables at inspection time, such as: uniformity and proportioning in concrete mixture, changes along the building, changes in cement, and others. These difficulties make the inspection work more interesting, yet more difficult.

2.2. Sampled areas

To understand the data presented in the next items, it is necessary to know the exposure differences and how the choice for each pillar was made for this work of inspection. It is important to emphasize that it was essential to visit the building on a dry day and on a rainy day and the authors consider this a standard procedure to make a sampling plan of an on-site work like this one.

2.2.1. Ground level pillars

On the ground floor, there are pillars that tend to have rain water ponding and others where this does not happens (see Fig. 2). This happened due to drainage deficiency on the ground floor slabs. For this reason, we opted for sampling involving both cases. In addition, pillars facing different sides of the building were analyzed to verify if there orientation to the sea had some influence.

After that, two groups of pillars were selected:

Group 1: pillars located on the ground floor where almost no water ponding occurs (P2 and P5). Moreover, within this group, P2 is oriented towards the sea and P5 is not. *Group 2:* pillars with water ponding after rainy periods, increasing the wetting and drying cycles (P1, P8 and P11). Within this group, there is a pillar facing the sea (P1) and two others not facing the sea (P8 and P11). It was important to compare the influence of wetting and drying cycles and the pillar orientation in relation to the sea.

Summarizing, five out of the thirteen pillars of the building were chosen, as shown in Fig. 1, considering the position in relation to the coastline. Two pillars facing the coastline were sampled (P1 and P2), and the other three were distributed in order to have one for each side of the building (P5, P8 and P11).

It is worth stressing that the pillars that presented corrosion reinforcement problems were located on the ground floor indicating a high degree of corrosion, as shown in Fig. 3.

2.2.2. Pillars along the height

In this case, some floors were sampled. Above the ground floor, no pillar did not tended to accumulate rainwater because they were protected by the building wall. However, the same pillars sampled on the ground floor were used in the sampling. In this way, a comparison of height influence and orientation in relation to the sea were investigated.

The levels sampled were the ground level and the 1st, 2nd, 5th, 9th, 18th and 27th.

2.3. Half-cell corrosion potential (E_{corr})

The corrosion probability was estimated in accordance with ASTM C876 standard [20]. The method is used to locate points where corrosion must be under development but without apparent manifestation. The classification criteria adopted are in accordance to ASTM C876 [20] and are reproduced in Table 1.

The reference electrode of the values shown in Table 1 is related to copper/copper sulphate (CSE).

2.4. Corrosion rate (I_{corr})

The corrosion rate was determined using the equipment called GECORR applying the linear polarization resistance technique to estimate corrosion rate. The classification criteria were indicated by Andrade et al. [21] and are reproduced in Table 2.

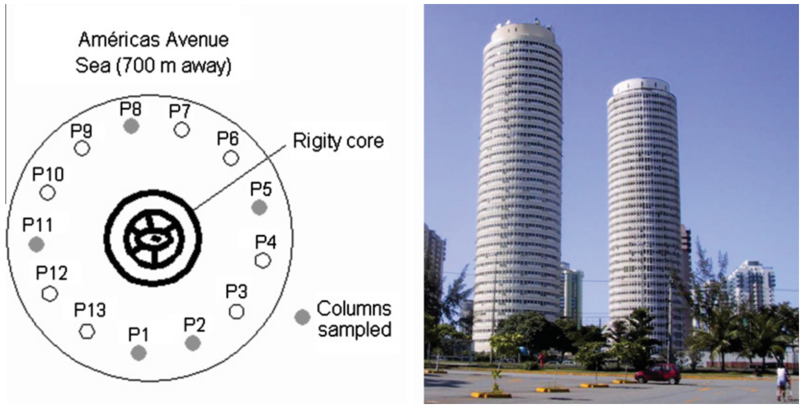

Fig. 1. Building overview and sampled pillars position in relation to the coastline.

(a) P2 column, without water ponding. (b) P8 column, with water ponding.

Fig. 2. Water ponding around some pillars of the ground level.

(a) corrosion at the column base at the ground level. (b) corrosion cell formed.

Fig. 3. Deterioration of the pillars on the ground floor.

2.5. Chloride content

In marine environments, reinforcement corrosion is directly related to the chloride content in the concrete near the steel surface, which should not be greater than 0.4% in relation to the cement mass for reinforced concrete structures [22].

The total chloride content (free + combined) was determined in accordance to ASTM C 1152 [23]. The samples used were carefully extracted from the studied pillars and correspond to the range of 15–20 mm in depth from the pillar surface. The depth was chosen because this is the average concrete cover range of the studied pillars.

Table 1
Ranges of half-cell corrosion potential related to the corrosion probability [20].

Corrosion potential (E_{corr}) (mV vs. CSE)	Corrosion probability
⩽−350 mV	90%
(−350 mV)–(−200 mV)	Uncertain
>−200 mV	10%

Table 2
Corrosion rate related to corrosion level [21].

I_{corr} (μA/cm^2)	V_{corr} (mm/year)	Corrosion level
⩽0.1	⩽0.001	Negligible
0.1–0.5	0.001–0.005	Low
0.5–1	0.005–0.010	Moderate
>1	>0.010	High

2.6. Compressive strength

The compressive strength was determined by the removal of 75 cores from the different studied pillars. This test was conducted in accordance with the Brazilian standard NBR 5739 [24] for cylindrical specimens (10 × 20 cm) and using a loading speed of 0.5 MPa/s.

2.7. Immersion absorption

The immersion absorption test was conducted according to Brazilian standard NBR 9778 [25].

The procedure consisted in determining the dry weight (obtained by drying the specimen to 70 °C until the mass was constant) and the saturated weight, obtained by keeping the samples with 1/3rd of their volume immersed for 4 h, then 2/3rds in 4 subsequent hours and resting completely immersed during 64 h. The saturated weight is the value obtained after 72 h immersed and with the surface dry, using absorbent material. With the difference between saturated weight and dry weight, the water percentage absorbed by the concrete was calculated.

3. Results and discussion

3.1. Compressive strength and immersion absorption

The two tests are presented here to characterize the studied concrete pillars. Fig. 4 shows the average compressive strength for each level, that varied between 29 MPa and 45 MPa and it is clear that the higher values occurred in ground and first levels. This is consistent because those are the levels with larger loading. However, the values did not follow the logic of increasing or staying constant from the lowest level to the highest one. Furthermore, Fig. 4 shows a high variability in data related to the average value. This may be a sign of low quality control implemented in this building that was made in the 1970s, a time when, in Brazil, the execution control standards were still undeveloped.

The project resistance values on that time went from 15 to 20 MPa. Besides, quality control was low and this probably was compensated with the specification of concretes with much higher compressive strengths than the one considered in the structural calculation. It was an uneconomical conduct, however favoring safety and needed due to the large quality variability of the concrete used in the construction site.

Fig. 5 shows results of immersion absorption for each pillar. The values are between 4.8% and 6.3% and correspond to low-absorption concrete. This is related with what was previously explained, that the concrete was over dimensioned somehow to compensate the large dispersion of concrete quality. This, somehow, resulted in the reinforced concrete suffering lower degradation during this exposition period in an environment close to the sea.

3.2. Chloride-ion contents

3.2.1. Pillars at the ground level (wetting and drying cycles X position in relation to the sea)

This part of the work presents the results for ground floor pillars, where there are pillars oriented towards the four sides of the building including those facing the sea. Moreover, there are pillars submitted to wetting and drying cycles (P1, P8 and P11) and pillars not submitted to wetting and drying cycles (P2 and P5).

Fig. 6 shows that the highest chloride contents occur in pillars submitted to wetting and drying cycles (P1, P8 and P11). This indicates that this is a highly relevant factor concerning ion penetration in a reinforced concrete structure. This is in accordance with data found by Meira et al. [11] and Costa and Appleton [26].

Pillar orientation does not seem to greatly influence chloride penetration because P2 did not present high level of chloride contamination even facing the sea. Thus, the data indicate that probably the occurrence of wetting and drying cycles is more important than the pillar position in relation to the sea.

It is necessary to make clear that this finding is specific of this inspection work, requiring more detailed studies to generate more accurate statements. This is due to the fact that it is a real structure in inspection work with limited execution time and investment, and a larger sampling was not possible. Yet, these results are an experience from a real case, although they should not be considered the absolute truth.

In fact, these considerations should raise new questions to be answered more precisely with studies involving a larger number of samples and isolating other variables that can affect results.

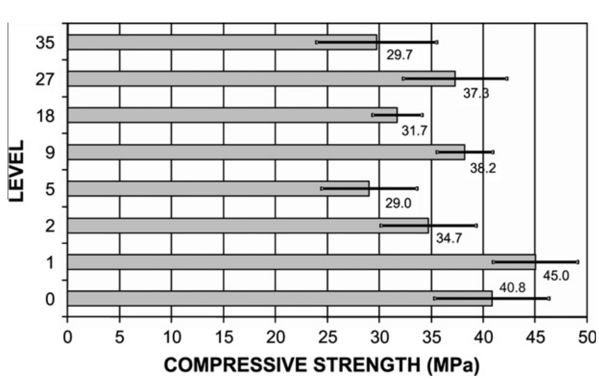

Fig. 4. Compressive strength for each level.

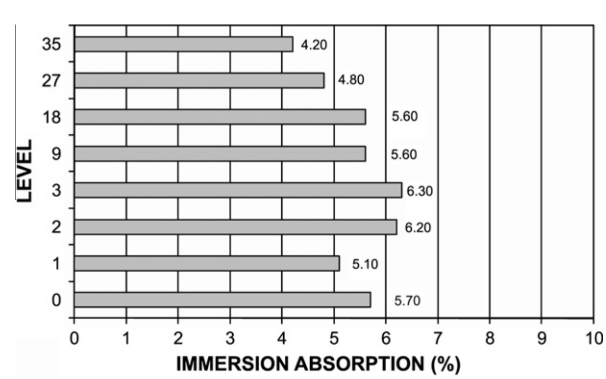

Fig. 5. Immersion absorption for each level.

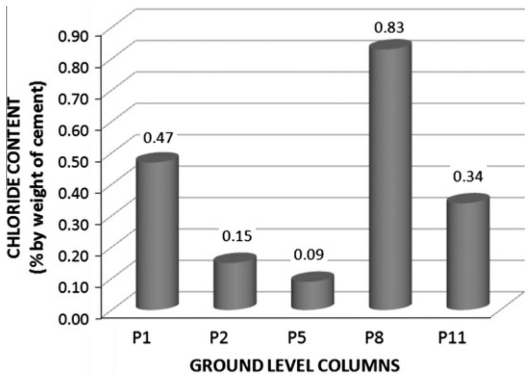

Fig. 6. Chloride content (by weight of cement) at ground level pillars.

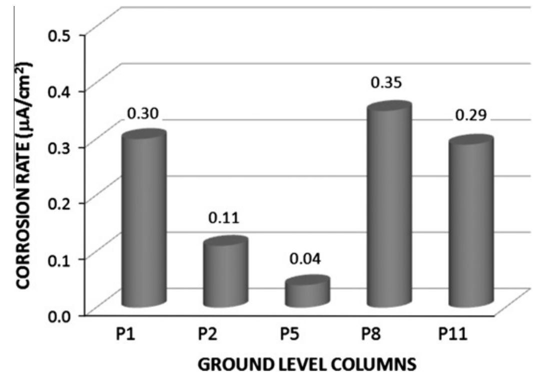

Fig. 8. Corrosion rate (µA/cm^2) at ground level pillars.

Furthermore, half-cell corrosion potential and corrosion rate data are in accordance with chloride contamination. Fig. 7 shows half-cell potential corrosion from the ground floor. It is clear that P2 and P5 have more positive half-cell corrosion potential (framed as a low corrosion probability) than pillars submitted to wetting and drying cycles (P1, P8 and P11). However, P1, P8 and P11 are classified in accordance with ASTM C 876 [20] as uncertain corrosion probability.

Concerning the corrosion rate reading, the data follow the same tendency, with pillars P2 and P5 classified as negligible corrosion level, while pillars P1, P8 and P11 are classified as low corrosion level (see Fig. 8).

3.2.2. Pillars along height (position related to the sea X height)

Another evaluation of this inspection work is chloride concentration along the height of each studied pillar. For this comparison, ground floor pillars results were excluded; in this case, there were pillars submitted to wetting and drying cycles that have a totally different kind of micro-climate from the other floors. For this reason, in this section, results from each evaluated pillar between the first and twenty-seventh floors are presented, comparing only pillars without wetting and drying cycles caused by the incidence of rain.

Fig. 9 presents the chloride content results obtained from the different pillars at each sampled levels. Compared to results obtained from the ground level, it can be seen that the chloride contents of this level are far higher than those found on other levels, a fact probably associated to water ponding occurring around the pillars base, originating wetting and drying cycles, which contribute to the easier ingress of chloride-ions [7], as can be seen in Fig. 2.

The results of Fig. 9 show that the greater the height, the lower the chloride content level related to cement mass is. This does not happen in all the cases, but it is to be expected, because it is a real structure built 40 years ago. These discrepancies can be caused by changes inherent to any construction process.

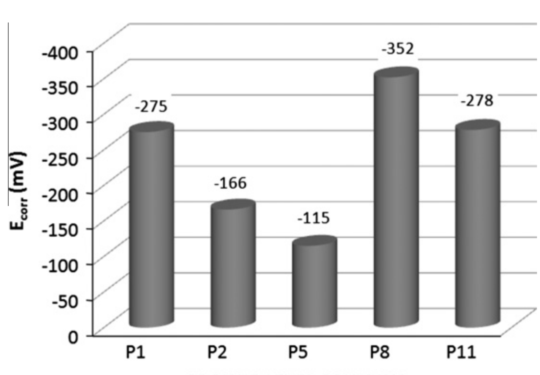

Fig. 7. E_{corr} (mV) at ground level pillars.

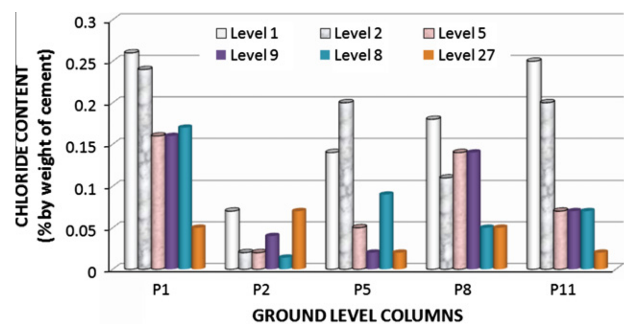

Fig. 9. Chloride content (by weight of cement) *X* levels (level 1–27 and pillars P1, P2, P5, P8 and P11).

Fig. 9 shows that another important issue to be highlighted from these data is that again the position in relation to the sea was not a high influence factor in the contamination degree of the structure. P2 had lower chloride content as compared to others pillars and P1 had the same level of chloride content as the others pillars.

4. Concluding comments

The results presented in this work make it evident that, besides the distance from the sea, height is another factor of great influence in the intensity of attack by chloride ions. Furthermore, the orientation in relation to the sea showed no influence on the contamination of the studied pillars.

Among all the chloride-ion contents determined, the only ones able to depassivate the steel rebar were found in pillars P1 and P8 at the ground level, being of 0.47% and 0.83% in relation to the cement mass, respectively. The other chloride-ion contents reached, at most, 0.34% in relation to the cement mass, even after 40 years of exposure to weather without any sort of protection and at a distance of 700 m from the coastline. This is in accordance with the results found in the literature [5,9–11] which show that the intensity of the attack is severely reduced with increases in distance from the coastline. It is an important aspect, indicating that service-life models and building standards should consider this effect.

Another observation of this work is that on floors where water ponding did not occur (wetting and drying cycles), the chloride ion contents were observed to have a tendency to decrease at higher places.

Hence, it was clear that the deterioration rate observed in these defective structures depends mainly on the exposure conditions of each part of the structure (microclimate). Moreover, the strong effect of the wetting and drying cycles on the chloride-ion content was verified, and chloride contents of about 3 to 8 times higher than the ones found in cases where wetting and drying do not exist were found at ground level. This process is explained by the mechanism of contamination of a concrete structure in marine environment. The chloride ions in the air are deposited by impaction on the concrete surface and the water from rain dissolves chloride ions and transport them to the interior of the structure through mechanisms such as capillary absorption or diffusion.

It is important to highlight that the considerations made here need validation supported by a more detailed experimental study. This is due to the fact that in a real structure there are several variables that are not controlled. Thus, this work results should be seen as a reference of a particular experience that triggers laboratory studies. The aim is to set questions to conduct new studies and contribute to the advance of civil engineering.

Acknowledgements

The authors would like to thank the Escola Politécnica of the University of São Paulo (POLI-USP) and the Federal University of Paraná (UFPR) for making this study possible.

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