



Determining corrosion levels in the reinforcement rebars of buildings in coastal areas. A case study in the Mediterranean coastline



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HIGHLIGHTS

- The corrosion levels of a building's structural elements were analyzed by optical and electron microscopy.
- The shows the result of corrosion *in situ* in a real structure.
- The building had been put up in 1968.
- EDX was used to analyze the condition of the reinforcement surfaces.
- It is verified the presence of crystals of at least akaganeite, lepidocrocite and goethite.

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ABSTRACT

This paper describes a study of the damage caused by corrosion to the reinforcement rebars of a 40-year old building used as a car park at a distance of 20 m from the sea. The corrosion levels of the building's structural elements, including beams, joists and columns were analyzed by optical and electron microscopy. Carbonation depths and chloride contents (Volhard method) of the concrete cover were measured *in situ*. EDX was used to analyze the condition of the reinforcement surfaces and the morphology and composition of the oxides. A high degree of corrosion was observed in all the above elements, carbonation had reached the depth of the reinforcement in all the samples studied, and the concrete chloride levels were far in excess of the recommended maximums. The study of the reinforcement rebars revealed different types of oxides of varying morphologies, compaction and coloring according to chloride content. A comparison with previous studies allowed us to verify the presence of crystals of at least akaganeite, lepidocrocite and goethite.

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1. Introduction

The Valencia coastline has been a leading tourist region in Spain since the nineteen-sixties and its popularity has given rise to the massive construction of residential buildings in the area. Many of these have been raised close to beaches, where this was possible, at between 10 and 20 m from the waterline. Being so close to the sea, the buildings are exposed to the marine environment and in many cases also to the direct effect of the marine aerosol.

The main cause of the loss of durability in coastal buildings is the corrosion of the reinforcement rebars due to the chloride ion effect [1], which is often found in combination with carbonation processes [2]. Both phenomena contribute to the destruction of the passive film on the surface of the reinforcement existing in the steel surface protected to the corrosion.

Salt particles suspended in the marine atmosphere are deposited on the surface of the concrete and the chloride ions then penetrate to the interior, where there is a strong likelihood of them corroding the reinforcement. The rate of the deposit depends on the saline content of the sea breeze and is rapidly reduced with distance from the sealine. Some studies have shown that there are different concentration levels in the salt spray zone in relation to distance from the shore line, especially in the first 200 m [3]. The chloride ions build up faster than atmospheric carbon dioxide (which is responsible for carbonation of the concrete), so that the action of chlorides is usually the chief factor in the corrosion of reinforcement in this type of atmosphere, when the structure is exposed to a sea breeze.

The depassivating effect of chloride ions becomes apparent when a threshold value of chloride concentration is reached in the concrete. Factors that influence this threshold value include atmospheric conditions such as moisture content, the presence of oxygen, and period of exposure to the marine environment, as well

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as aspects related to the composition of the concrete, including: different conditions of the reinforcement passivation, water/cement ratio, type of cementitious matrix, and hydroxide content of the porous network [4,5].

Distance from the sea is an important factor in the quantity of salt particles deposited on a surface and therefore also in their reaching the reinforcement. In addition, the wetting–drying cycles of the concrete affect the content of chloride ions, which can be from 3 to 8 times higher when these cycles are absent [6].

Although there are many bibliographical references on different aspects of the durability of reinforced concrete in marine environments, most studies on corrosion in reinforced concrete structures were either carried out in the laboratory or samples were subjected to accelerated exposure in controlled environments. Also, few studies deal with concrete structures exposed *in situ* to long-term marine environments. To cite some examples: De la Fuente [7], Santana [8] and Castaño [9], among others, studied the effects of long-term exposure (13 years, 2 years and 14 months, respectively), under different atmospheric conditions, but on samples of steel; Poupard [10] studied reinforced concrete beams that had been in a tidal marine zone for a period of 40 years; Medeiros [6] studied the parameters that affect corrosion in the columns of a 37-storey building with two basements situated 700 m from the coastline.

In the marine environment, depassivation of the reinforcement can lead to the formation of an irregular layer of oxide on the steel/concrete interface. The thickness and composition of the products in this layer have been widely studied by various authors, all of whom agree that it is mostly composed of non-protective iron oxides and oxyhydroxides. Poupard et al. [10] state that the thickness increases with the degree of corrosion, varies between approximately 20 and 500 μ , and that its composition depends on the degree of damage it has sustained; for “low corroded” regions it is composed solely of magnetite (Fe_3O_4), while “high-corroded” regions contain goethite ($\alpha\text{-FeO}(\text{OH})$), maghemite (Fe_2O_3) and akaganeite- $\beta\text{-FeO}(\text{OH}, \text{Cl})$. Oh et al. [11] point out that when the same type of steel is exposed to different ambient conditions, the characteristics of the corrosion products vary in relation to different ambient conditions. However, they also found that certain corrosion products are always present, regardless of the environmental conditions and type of steel studied.

The location of different crystalline phases in the oxide layer has also been thoroughly studied; in particular for highly corroded steel, different authors found this layer to be composed of different sublayers [12,13]. Shiotani et al. [12] studied steel that had been exposed to a marine atmosphere for 27 years and after examining the samples by polarized optical microscopy, found that the internal zones appeared to be constituted mainly of magnetite and goethite, besides an amorphous substance, while the outer layer contained lepidocrocite ($\gamma\text{-FeO}(\text{OH})$) and occasionally akaganeite. Duffo et al. [13] in their work on a bar embedded in concrete that had been exposed for 65 years to an atmospheric environment found that the inner layer was formed chiefly by adherent non-stoichiometric magnetite and the outer layer of lepidocrocite and goethite. The formation of dense products in the oxide layer due to goethite, magnetite or maghemite only occurs in the presence of carbonation [10,13] but not when attacked by chlorides. Magnetite is developed in the vicinity of the steel surface where oxygen availability is lower [7,14].

As a number of authors have pointed out [10,14,15] lepidocrocite and magnetite are generally formed in the early stages of atmospheric corrosion. The lepidocrocite content usually diminishes with time, as it changes into goethite after prolonged exposure [15].

In the highly corroded areas, goethite is present in the oxide layer, especially in the external sublayer. Akaganeite becomes pre-

sent in the oxide layer at high chloride concentrations [7,15–17]. Ma et al. [15] verified that the presence of Cl^- and therefore of the akaganeite phase, is an indicator of high corrosion rates.

Crystal morphology depends on the conditions under which crystals are formed. Lepidocrocite is frequently found in the form of small crystalline globules (sandy crystals) or as fine plates (flowery structure) [7,9,15]. Goethite morphology usually has a globular structure known as *cotton balls* (semicrystalline goethite) connected by nest-like formations (nest morphology) or even by acicular structures (crystalline goethite). Magnetite is found in the form of dark flat regions, with hard-to-identify circular discs, while akaganeite can take the appearance of cotton balls or be rose-shaped [7]. As can be gathered from the above studies, the different crystal morphologies have a strong influence on their degree of compactness and therefore on their porosity and the ability of moisture and air to get inside [18].

The different morphologies of the iron oxides and oxyhydroxides found in corrosion affect not only compactness and porosity but also the volume of the layer, and so have different expansive effects on concrete. Many authors, e.g. Cascudo [19], pointed that iron oxides (II) and (III) have approximately twice the volume of the steel from which they proceed. In addition, if the oxides are hydrated (oxyhydroxides), the volume can be up to four times greater and could give rise to the formation of lepidocrocite, goethite or akaganeite, which would make fissures appear in the oxide layers themselves.

This paper studies the state of corrosion of the reinforcement rebars of different reinforced concrete structural elements: columns, beams and joists in a building situated 20 m from the edge of the sea after long-term exposure (45 years) to a marine atmosphere, including the identification of the type of attack suffered and the morphology of the corrosion products. The novel contribution of this work is that it shows the result of corrosion *in situ* in a real structure exposed to an aggressive marine environment for a long period and its correlation with the controlled atmospheric conditions described in the bibliography.

2. Materials and methods

2.1. Description of the structural elements studied

Specimens were taken for subsequent laboratory tests from a building in Cullera (Spain) that was being completely rebuilt and situated 20 m from the coastline ($39^\circ 10' 51.6''\text{N}$ $0^\circ 13' 09.1''\text{W}$). The building structure was composed of reinforced concrete frames with floor slabs and the tests were carried out on beams, joists and columns.

The building in question had been put up in 1968 and was used as a car-park. The façades were of non-waterproof lattice-work construction, which allowed the salt spray to get inside and on windy days the walls could even be splashed by sea-water spray from high waves.

2.2. Characteristics of the local environment

Cullera is in the Mediterranean climatic region. Average annual temperature is 17 °C, ranging from 11.2° in January to 25.9° in July. Annual rainfall is 475 mm per square metre [20]. The prevailing wind is from the east-northeast at an average speed of 6.5 kph. The temperature of the sea water varies between 12 °C in winter to 24–25 °C in August and September.

The building is beside the coast at 16 m from the water line and 10 m above sea level in uneven rocky terrain. The entire building is exposed to a greater or lesser degree to the marine environment and in stormy conditions the sea spray is blown into the building through the lattice walls.

2.3. Samples

This paper contains the results of the tests on the most severely corroded samples. The information obtained from optical (SM) and electron (SEM) microscopy pertains to specimens taken from columns in the outer wall and floor beams and joists that had been subjected to natural wetting–drying cycles

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