Effect of chloride-induced corrosion on the mechanical properties of galvanized carbon steel anchor rods of guyed power transmission line towers

Tiago Scheffer Matos[1, 2]
Kleber Franke Portella[1, 2]
Mariana D´Orey Gaivão Portella Bragança[1]
Bruno Endo Ribeiro[1]
Alessandro Cesar de Sousa Berrêdo[3]
Sérgio Luís Henke[4]

[1]Institutos Lactec- Departamento de Estruturas Civis
tiago.matos@lactec.org.br
portella@lactec.org.br

[2] Universidade Federal do Paraná - Programa de Pós-Graduação em Engenharia e Ciências dos Materiais-PIPE

[3]Transmissora Aliança de Energia Elétrica S. A./TAESA

[4] Universidade Federal do Paraná - Departamento de Engenharia Mecânica

Abstract: Corrosion of anchorage systems of power transmission towers installed in aggressive environments is one of the major causes of the loss of their service life, often associated with premature failure. However, compatibility analysis of the materials with the environment is often not performed. In this study, the concentration of chloride ions in the cement paste was measured along the surface of the anchor rods retained in the field, as well as the composition of the steel and its mechanical properties in corroded and uncorroded states. The anchor rod with the intermediary concentration of chloride ions had the greatest loss of their cross-section and of the mechanical properties of the material. The microanalysis by field emission gun, scanning electron microscopy (FEG-SEM) indicated the loss of galvanized protection on the metal surface.

Keywords: anchor rods, corrosion, chloride, microanalysis, power transmission towers.

1 Introduction

One of the major challenges has been to increase the service life of metallic materials in concrete structures. Durability problems caused by the premature deterioration of concrete structures (bridges) and also of the anchoring system of guyed power transmission line towers (anchor rods encapsulated in cement paste) have caused high expenses with maintenance and repairs. A study commissioned by the Federal Highway Administration (FHWA) [1] estimated that the annual cost of corrosion of metallic materials in the USA was approximately 276 billion dollars, of which approximately 600 million dollars were spent on the maintenance of transmission and distribution lines [1].

The presence of chloride ions is a major cause of the deterioration of concrete structures in the presence of sufficient amounts of water and oxygen [2]. Chloride ions dissolved in water pass through microcracks, or concrete slits, and reach the steel bars by means of diffusion processes. These ions pass through the passive layer of the steel bar and react at the metal surface [3][4].

In a recent study, researchers have shown the effects localized corrosion on the mechanical properties of concrete structures after exposure to an atmosphere with chloride ions. A significant loss of the mechanical properties, mainly ductility, of the steel embedded in concrete was evidenced in relation to the steel exposed directly to the corrosive environment [5].

Several studies have been carried out with the objective of determining the concentration of chloride ions that induce corrosion in steel. Angst et al. [6] introduced the concept of chloride threshold level (CTL). However, there is no consensus about CTL and the correlation with the deterioration of the structures, because the CTL can be affected by many factors [6][7].

The durability of anchor rods, especially those exposed to aggressive environments, is important, mainly due to safety and economic factors. The occurrence of failure on the anchorage system may lead to the fall of the transmission tower and consequently the interruption of the electric power supply [8]. One of the main difficulties of evaluating the integrity of buried anchor rods is how to access them.

The aim of this work is to report the investigation of mechanical properties and the microstructure of galvanized carbon steel anchor rods of a transmission line in the Northeast of Brazil and correlate them with the chloride ions concentration present in cement paste on their surfaces. From these results, it is possible to evaluate the relationship between these properties and predict the corrosion level that reduces the service life of anchor rods. Moreover, the knowledge of these parameters can help in the selection of materials, as well as reduce the risk of premature failure.

2 Materials and methods

The work is subdivided into five stages: sample preparation, measurement of chloride in cement paste, tests for mechanical properties, evaluation of the microstructure of galvanized carbon steel anchor rods and chemical composition.

2.1 Sample preparation

Sampling of the cement paste was carried out along the surfaces of three anchor rods pullout from different power line towers installed in the state of Rio Grande do Norte. Samples with corrosion process were collected and identified as 1.0865.17, 1.0875.17, 1.0876.17, and are show in Figure 1.

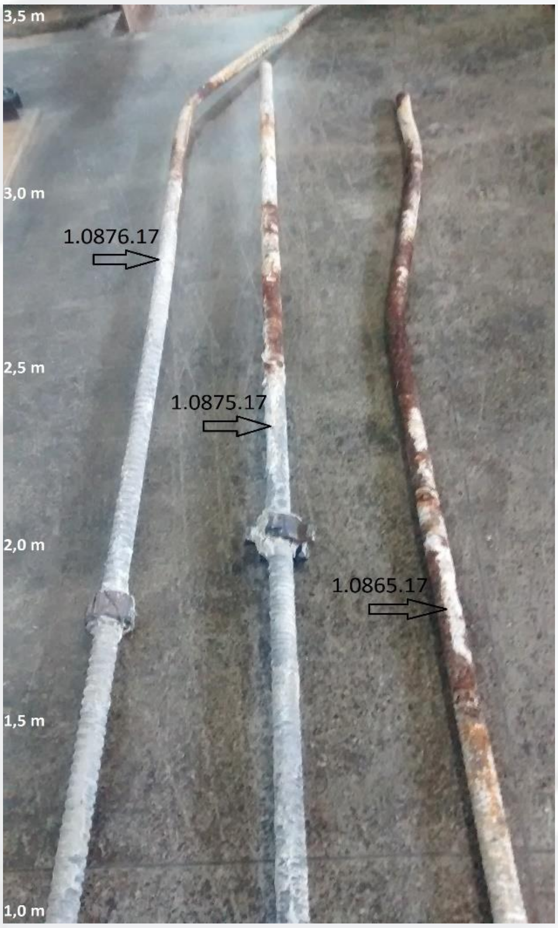

Figure 1: Three different anchor rods removed from the transmission line towers installed in the state of Rio Grande do Norte. The arrows point to cement paste on the corrosion region.

2.2 Chloride

The concentration of chloride ions (Cl^-) was measured in the cement paste, after extraction by ASTM C1218-15 [9], using an ion chromatography system, 882 compact IC plus Metrohm, with suppressed conductivity detection.

2.3 Mechanical properties

The tensile tests on anchor rod samples were performed in accordance with ISO 6892-1 (ABNT, 2013) [10], using an equipment Wolpert-Amsler, Testa model 600 kN, electro hydraulic type, maximum capacity of 60,000 kgf. Sections of 60 cm^2 were removed from each anchor rod, in the regions where the cement paste sample was collected for the analysis of chloride (Figure 1) and in the upper part where it had no signs of corrosion. To calculate the yield strength, the offset method was used, as ABNT NBR ISO 6892-1 recommends.

2.4 Evaluation of microstructure

The microanalysis was carried out using a scanning electron microscope, type FEG (field emission cannon), model Mira3 LM, Tescan with energy dispersive X ray spectroscopy (EDS) for elemental analysis and backscattered electron detector (EBSD) model NordlysNano from Oxford Instruments, which collects crystallographic information. The samples were polished beforehand using 600 and 1200 sandpaper for 5 min each and then polished in the Ion Mill SC-1000, SEMPrep, of the Technoorg Linda. The purpose of this procedure was to reveal grain boundaries and to improve the indexing of crystalline phases.

2.5 Chemical composition

The chemical composition was made in an optical Emission Spectrometer for Metal Analysis, model Q8 MAGELLAN from Bruker elemental.

3 Results and discussion

This section presents the results obtained as well as brief discussions.

3.1 Chloride and mechanical properties

The content of free chloride ions in cement paste ranged from 258.86 to 1025.60 mg/kg in the samples analysed. Figure 2 shows results of the free chloride in the cement paste removed from anchor rods.

As mentioned by Angst et al. [6] the concentration of chloride ions in the cement paste can be correlated with the process of depassivation on the metal surface and with the beginning of deterioration of the material.

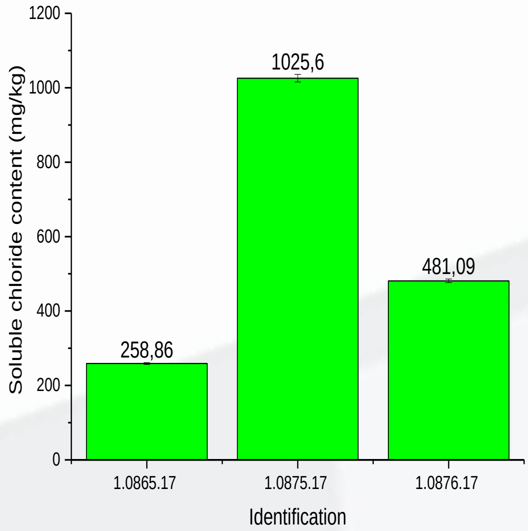

Figure 2: Soluble chloride content in cement paste located on the surface of galvanized guy anchor rods.

Results for anchor rods mechanical properties, shown in Table 1, were obtained in the tests carried out in corroded and uncorroded galvanized steel samples.

Table 1: Tensile properties for corroded and uncorroded anchor rods and depth ground section analysed.

Identification	Yield strength (MPa)		Ground depth of corroded section analysed (mm)
	Uncorroded	Corroded	
1.0865.17	605.0	586.6	1.50 - 2.10
1.0875.17	583.0	546.5	2.00 - 2.60
1.0876.17	516.5	428.7	2.50 - 3.10

The corroded anchor rod had a loss of section, due to iron oxides products formed during the corrosion of carbon steel, so the small section influenced the yield strength and the ultimate tensile strength. The uncorroded bar, Figure 3, has the ductile fracture, with an elastic and plastic region before the fracture, similar de the low and medium carbon steels [7]. Moreover, the corroded anchor had the brittle fracture, as shown in Figure 4. The red lines in Figures 3 and 4 were used to calculate the yield strength, based on the ABNT NBR ISO 6892-1 recommendation.

The higher level of chloride was measured in the sample 1.0875.17 in the intermediate conditions of depth, and the less concentration was obtained in the sample 1.0865.17 on the surface of cement paste.

The difference in chloride content in the cement paste was attributed to the water table, with saline water, as brackish water.

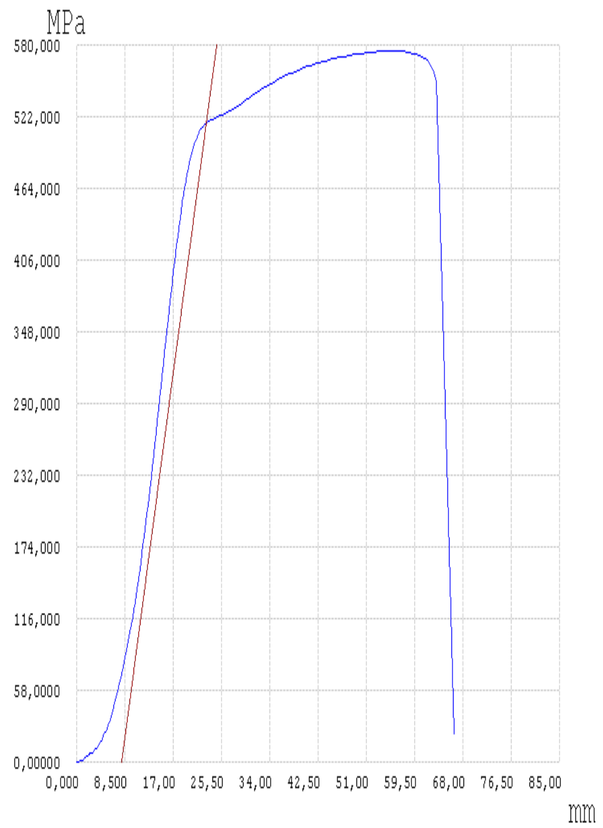

Figure 3: Yield strength of uncorroded galvanized guy anchor rod extracted of field, 1.0876.17.

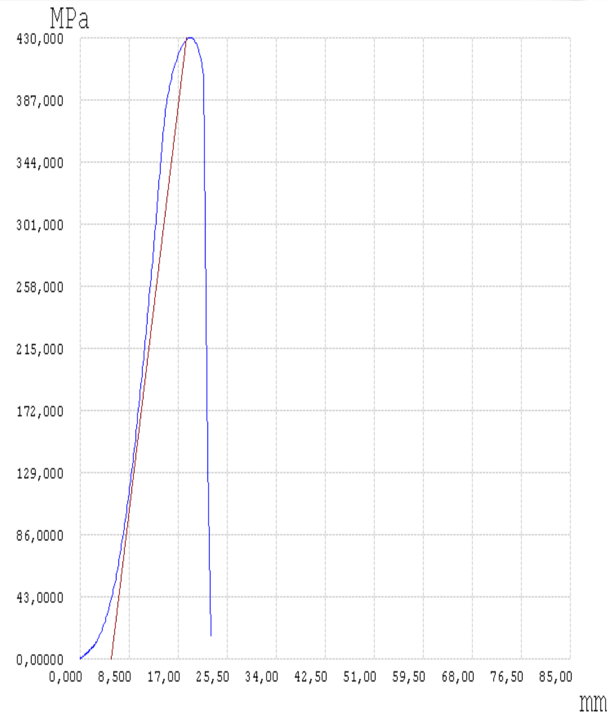

Figure 4: Yield strength of corroded anchor galvanized guy anchor rod extracted of field, 1.0876.17.

3.2 Microanalysis

The microstructure of the galvanized carbon steel anchor rods obtained by FEG-SEM (EBSD) can be visualized in Figure 5. The size and orientation of grains were uniform, well distributed and very similar in all samples.

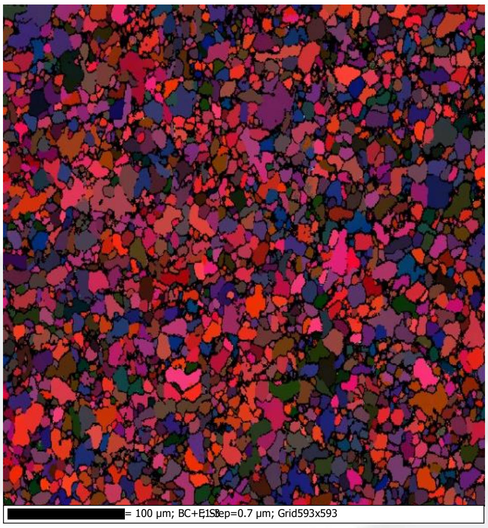

Figure 5: FEG-SEM - EBSD image of grains of transmission line tower anchor rod carbon steel analysed, 1.0876.17.

The surface images of the galvanized carbon steel showed the loss of the zinc film in sample 1.0876.17 while the sample 1.0875.17, with the highest chloride content among the three samples (1025.6 mg / kg), remained intact in the sample as shown in Figure 6 (A) and (D), and highlighted in Figure 6 (B) and (E). This indicates that not only the high concentration of chloride (sample 1.0875.17) was able to break the protective layer of the zinc film in the galvanized steel, but also that other factors such as humidity and difference in oxygen content combined could have a greater impact on this corrosive process [13][14], as indicated in the literature, [7][15]. This may explain the fact that sample 1.0876.17 had the greatest loss of mechanical properties.

The sample 1.0865.17 had the best results in relation to the chloride content and the mechanical properties both in the corroded and non-corroded region.

The presence of sodium in sample 1.0876.17 could be due to the salts dissolved in the cement paste which may have adhered to the surface of the metal.

The FEG-SEM images of qualitative chemical composition analysis in the corroded and uncorroded areas, Figure 6 (C-F), show that the zinc barrier was consumed by corrosion. This fact was in agreement with the mechanical properties losses [12]. The analysis of uncorroded anchor rod, as shown in Figure 6 (F), presented an intact protective barrier of zinc on the surface.

3.3 Chemical composition

Chemical composition average of the anchor rods are shown in Table 2. The chemical composition correspond to carbon steel SAE 1526 or SAE 1527.

Manganese additions lead to a marked increase in hardness of the metal, but then the probability of the anchor rods to fail the mode brittle without signs of fatigue is larger [16].

Table 2: Chemical composition average of line transmission tower anchor rods by optical Emission Spectrometry.

Identification	Elements content (weight %)				
	Carbon	Silicon	Manganese	Phosphorus	Sulfur
Anchor rods	0,29	0,20	1,30	0,013	0,006

The presence of manganese in carbon steels, as illustrated in Table 2, increases hardenability and tensile strength of the material. It is also able to decrease the critical cooling rate during hardening, thus increasing the steels hardenability much more efficiently than any other alloying element. However, the higher the hardness of the material, the greater the possibility of brittle fracture without the observation of fatigue [17].

The silicon content affects the reactivity of iron with zinc in the metallurgical process. The diffusion of iron in the molten zinc, in high silicon content steels has a negative impact on the quality of the zinc coating. The silicon content within the limits defined by the range from 0.15 to 0.25% is acceptable for hot-dip galvanizing [18].

4 Conclusions

The critical concentration of chloride that induces corrosion depends on factors other than the amount of free chlorides in the cement paste measured in the samples studied. This was confirmed by the fact that the 1.0875.17 sample with the highest chloride content (1025.6 mg/kg) had results of mechanical properties close to sample 1.0865.17 with the lowest chloride content (258.76 mg/kg).

The loss of the passive zinc film in the region analyzed in sample 1.0876.17 with the intermediate chloride value (481.09 mg / kg) may be due to the fact that the region analyzed is the deepest and possibly the highest water content in the soil, which potentiates the effect of the chloride ion on corrosion.

The presence of chloride ions in the cement paste may be caused by the penetration of the ion through the pores of the cement slurry or even by the use of contaminated water in the production of the slurry used to encapsulate the anchor rods.

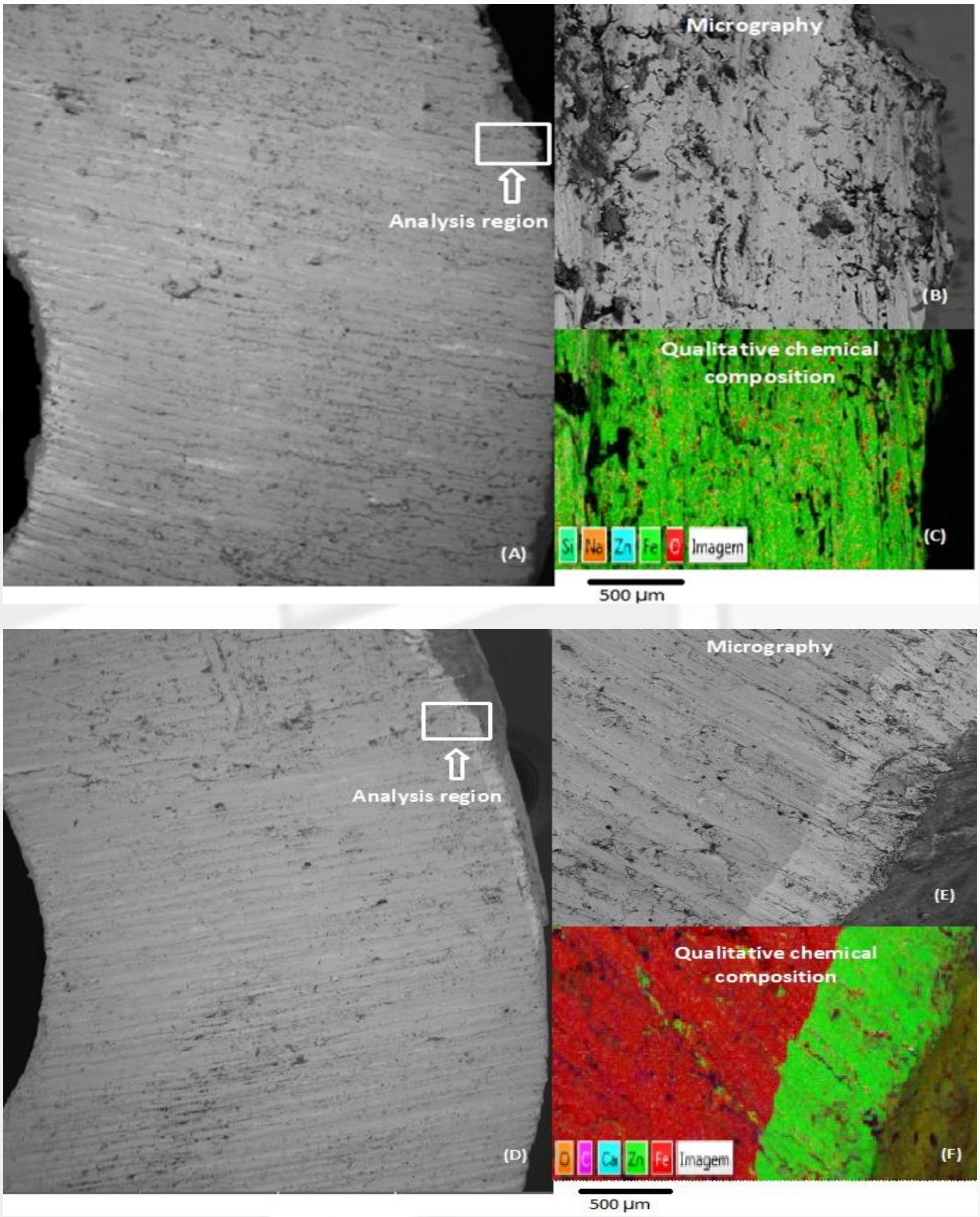

Figure 6: FEG-SEM images of sample 1.0876.17 (A) (B) (C) without film of zinc on the anchor rod surface after the corrosion process and SEM images of sample 1.0875.17 (D) (E) (F) with galvanized protection in the uncorroded area.

Acknowledgements

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