Electrochemical characterization of corrosion in materials of grounding systems, simulating conditions of synthetic soils with characteristics of local soils

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Abstract. The integrity of structures buried in earthing becomes relevant when analysing maintenance and replacement costs of these systems, as the deterioration is mainly due to two factors, namely: the failures caused in the electrical systems, which are due to the system. Failure in earthing due to corrosion at the interface cause an alteration in the structure of the component material and generates an undesirable resistivity that cause malfunction in this type of protection systems. Two local soils were chosen that were categorized as sandy loam and clay loam type, whose chemical characteristics were simulated by means of an electrolyte corresponding to the amount of ions present determined by a soil characterization based on the CICE (effective cation exchange coefficient), which allows us to deduce the percentage of chloride and sulphate ions present for the different levels established in the experimental matrix. The interaction of these soils with grounding electrodes is a complex problem involving many factors to consider. In this study, the rates and corrosion currents of the different soils on two types of electrodes, one copper and the other AISI 304 stainless steel, were approximated by electrochemical techniques such as potentiodynamic curves and electrochemical impedance spectra. Considerably higher speeds were determined for copper-type electrodes when compared to those based on steel. However, from the Nyquist diagrams, it was noted that copper electrodes have better electrical performance than steel ones. The soil with the highest ionic activity turned out to be the sandy loam. The clay loam soil presents a tendency to water retention and this may be the reason for the different behaviour with respect to ionic mobility. The diffusion control in the steel seems to alter the ionic mobility because its corrosion rates proved to be very similar regardless of the type of soil chemistry. In general, corrosion rates fell since tenths of a millimetre every year to the hundredths of a millimetre in the case of the steel-based electrode, which are relatively small corrosion rates.

1. Introduction
Any electrical installation that follow the recommendations of RETIE [1] and IEEE Standards [6-15] has a grounding system, to prevent people near, electrical or electronic devices, can be subjected to high voltages of contact or transferred that surpass the thresholds of tolerance affecting the human body or damage electrical compounds when a fault occurs. The requirement of earthing for electrical installations covers the electrical system and give supports to metal structures that in the event of a
temporary overvoltage, can trigger a permanent fault between the earthing structure and the network. The objectives of a grounding system are: the safety of people, the protection of installations and electromagnetic compatibility [2-5].

In the procedure of earthing is necessary investigate the characteristics of the soil especially the resistivity. Within the tests that must be done as part of the inspection and as a requirement of evidence through records, must be recollected at least the following information: General conditions of the system conductors, corrosion level, state of the connections and conductors, electrical components and resistance values [6-7].

This work addresses the problem of comparing the degradation of the grounding electrode material from an approach chemical differentiation of elements present in each soil. It simulates soil chemistry through a very methodical approach designed specifically for this work. use salts that’s will separation in anions and cations, using a study of typical soils that determine the present cations, the possibility of having soils based on sulphates or based on chlorides is deduced to consider two types of corrosion operationally different.

2. Methodology

2.1. Electrodes composition
The copper composition was determined by X-ray florescence (MINIPAL 2), according to ASTM B 115. The stainless-steel composition was made by Optical Emission Spectrometry according to ASTM E 415 (Q8 MAGELLAN BRUKER QUANTRON).

2.2. Soils characterization
The corrosion evaluation was carried out by simulating the saline composition of two local soils, sandy loam and clay loam, supplementing them with chlorides and sulphates in adequate proportions. The characterization was performed by evaluating: texture, pH, hardness, cation exchange, electrical conductivity, percentage of organic matter, phosphorus, potassium, calcium and magnesium, in the UPTC soil laboratory. The resistivity of the soils was determined using the Wenner method.

2.3. Metallographic analysis of electrodes
It was performed using the DACE TECHNOLOGIES NANO 200 DT polisher, with grit # 80 to # 1200, the micrographs were evaluated on the LEICA DVM 2500.

2.4. Electrodes electrochemical test
Potentiodynamic evaluation was performed using a rotating ring electrode coupled to a galvanostat potentiostat (Gamry 750) [16], with a sweep of -250 to 250mV and a speed of 2mV/s.

3. Results and discussion

3.1. Soil resistivity

| Spacing (m) | Clay Loam Soil | Sandy Loam Soil |
|-------------|----------------|-----------------|
|             | Profile 1 $\rho(1)$ | Profile 1 $\rho(2)$ | Average Resistivity $\rho(\Omega \cdot m)$ | Spacing (m) | Profile 1 $\rho(1)$ | Profile 1 $\rho(2)$ | Average Resistivity $\rho(\Omega \cdot m)$ |
| 1           | 700.87 | 710.89 | 701.38 | 1 | 301.36 | 301.79 | 301.58 |
| 3           | 805.93 | 705.95 | 755.94 | 3 | 329.49 | 287.51 | 308.50 |
| 5           | 830.86 | 690.68 | 760.77 | 5 | 349.96 | 291.08 | 320.52 |
| 7           | 790.75 | 705.89 | 748.32 | 7 | 330.11 | 294.47 | 312.29 |
| 10          | 830.76 | 740.85 | 785.86 | 10 | 354.91 | 316.19 | 335.55 |
The average value of the resistivity measure for the clay loam soil was 750.45Ω m (Table 1), generating a resistance of 45.22Ω calculated by EIS method, in all cases the value was around 50Ω. For the sandy loam soil, the resistivity was 315.69Ω m and the resistance of 19.62Ω, with the IES method the value oscillates between 18 and 40Ω. These data indicate that electrolytic simulation of soils was acceptable and data that presented the greatest deviation, regarding the expected results was the stainless steel in loamy loam soil with base sulphate electrolyte.

3.2. Morphological properties of electrodes
The morphological evaluation showed that in the two soils with chlorides based electrolyte, corrosion by stinging was observed, being that it is more aggressive in the copper electrodes (Figures 1(a) and (b)) than in stainless-steel electrodes (Figures 1(C) and (d)).

![Figure 1. Electrode morphology. Micrographs and mappings with chlorides based electrolyte (a) sandy loam - copper (b) clay loam - copper (c) sandy loam - stainless steel and (d) clay loam - stainless steel.](image)

3.3. Potentiodynamic curves
The Figures 2 show that sandy loam soils present more negative potentials. The difference between corrosion potentials is around of 50mV and there are appreciable differences in the current densities of corrosion for the copper electrodes. The stainless-steel electrode shows a change in the potential corrosion greater than the copper electrodes. The most negative potentials correspond to the electrodes evaluated in soils with basic sulphate electrolyte.

![Figure 2. Potentiodynamic curves (a) copper electrode and (b) stainless steel electrode.](image)
3.4. Electrochemical impedance spectroscopy

The Bode graphs show the capacitive behaviour of the stainless steel (Figure 3(b)) that shows the presence of its passivation layer in contrast to the copper (Figure 3(a)) that presents minor variations in the phase angle. In Nyquist graphs the value of resistance of the solution is observed which are corresponded with measurement of resistivity in the field.

Figure 3. Bode Electrochemical Impedance Spectroscopy for (a) copper electrode (b) stainless steel electrode and Nyquist for (c) copper electrode (d) stainless steel electrode.

3.5. Circuits

The physical significance derives from the simple corrosion phenomenon that must be presented by the electrodes immersed in the solution that simulates the soil and therefore the CPE and Randles circuits (Figure 4) were chosen. The second circuit, chosen with diffusion, was tried to test due to the 304 steel electrodes, which when being stainless presented an anodic branch with considerable slope in the Tafel approximation, which was carried out on the potenciodynamic curves.

Figure 4. Equivalent circuits chosen. (a) CPE, (b) CPE with diffusion and (c) Randles.
Using the Gamry software, the parameters were deduced for each equivalent circuit, taking into account that Rp is the resistance value used in the calculation of corrosion rate in each case.

Table 2 compares the results for the different methods in terms of corrosion rate. The most similarity between the Tafel approximation of the potentiodynamic curves and the modelling made on the basis of the Randless circuit is observed in both the order of magnitude and its qualitative behaviour.

**Table 2.** Comparative synthesis of the calculated corrosion rates for each experimental treatment.

| Soil          | Tafel Corrosion rate | LPR Corrosion rate | EIS CPE modelling | EIS CPE diffusion modelling | EIS Randless modelling |
|---------------|----------------------|--------------------|-------------------|----------------------------|------------------------|
| SLC           | 0.875 0.0222 mpy     | 7.64 mm/yr         | 0.332 0.00843 mpy | 2.93E-17                   | 7.45E-19 44.6         |
| CLC           | 0.819 0.0208 mpy     | 4.16 mm/yr         | 1.143 0.02903 mpy | 1.16E-17                   | 2.94E-19 20.0         |
| SLS           | 0.740 0.0188 mpy     | 3.49 mm/yr         | 0.162 0.00410 mpy | 5.05E-18                   | 1.28E-19 22.8         |
| CLS           | 0.485 0.0123 mpy     | 2.02 mm/yr         | 2.770 0.07036 mpy | 2.75E-18                   | 7.00E-20 8.21         |
| SLC           | 0.243 0.0062 mpy     | 0.20 mm/yr         | 0.131 0.00333 mpy | 3.25E-18                   | 8.26E-20 0.480        |
| CLC           | 0.263 0.0067 mpy     | 0.21 mm/yr         | 0.127 0.00323 mpy | 1.70E-18                   | 4.32E-20 0.480        |
| SLS           | 0.227 0.0058 mpy     | 0.22 mm/yr         | 0.102 0.00259 mpy | 3.78E-19                   | 9.59E-21 0.564        |
| CLS           | 0.299 0.0076 mpy     | 0.22 mm/yr         | 0.117 0.00298 mpy | 1.49E-19                   | 3.77E-21 0.566        |

The corrosion rate, determined by Tafel approximations, shows lower values than those calculated with the Linear Polarization method, by an order of magnitude, although they have the same tendency. Steel electrodes have high anodic slopes suggesting that diffusion control is present. The corrosion rates of the stainless-steel electrode are always lower than those of copper.

**4. Conclusions**

The interface parameters of the materials in the simulated soils were evaluated using the EIS, LPR and Tafel approximation techniques for potentiodynamic curves. Resistivity measurements showed good simulation of the soils studied.

The electrochemical parameters were correlated with the factors used in the experimental matrix that defined the greater susceptibility to copper corrosion and the greater aggressiveness of soils in chloride electrolyte. The corrosion rate was determined using the electrochemical parameters obtained for the best models. The Tafel approximation presented lower values than those calculated by the LPR method, although with the same trend. The values obtained with the CPE approximation had the same order of magnitude as the LPR but with different behaviour. The results showed that sandy loam soil and the copper electrode present higher values of corrosion rate, chloride electrolytes are more reactive than sulphates and the stainless-steel electrode is more stable than copper electrode.

Copper exhibits poor corrosion performance but good electrical performance if RETIE standard is followed. The load transfer resistance value in stainless steel determines poor electrical performance if this type of electrodes is used in grounding systems.
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