Electrochemical techniques implementation for corrosion rate measurement in function of humidity level in grounding systems (copper and stainless steel) in soil samples from Tunja (Colombia)

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Abstract. In this work, DC electrochemical techniques were used to determine the corrosion rate of copper and stainless-steel electrodes used in grounding, varying the level of humidity, in sandy loam and clay loam soils. The maximum corrosion potentials were: for copper -211 and -236mV and for stainless steel of -252 and -281mV, in sandy loam and clay loam respectively, showing that in sandy loam the values are higher, about 30mV. The mechanism by which steel controls corrosion is by diffusion, whereas in copper it is carried out by transfer of mass and charge, which affects the rate of corrosion, which in copper reached a maximum value of 5mm/yr and in Steel 0.8mm/yr, determined by Tafel approximations. The behaviour of the corrosion rate was mathematically adjusted to an asymptotic model that faithfully explains the C.R. as a function of humidity, however, it is necessary to define the relation between the factor established in the model and the precise characteristics of the soil, such as the permeability or quantity of ions present.

1. Introduction
Among the electrical protection systems that exist against overload events, buried electrodes are a simple, economical and mass-use system in numerous electrical distribution systems both industrial and residential level [1-4]. In previous studies, the behaviour against corrosion of copper and stainless steel electrodes against sandy loam and clay loam was established, but it was only carried out with a moisture level [5]. The moisture level is perhaps the most relevant factor in the ionic conduction of corrosive agents such as sulphides and chlorides [6-8] the soils present considerable variation of this the level of humidity during its period of operation [9]. Therefore, it is necessary to determine the effect of moisture on the corrosion rate.

In a parallel work [10] to this one is standardized the electrochemical tests with synthetic soils designed to accurately simulate the behaviour of a determined soil. In contrast, in this work, the original soils extracted were used and their level of humidity varied, a procedure that is described in detail in the methodology.
It seeks to know in detail the problem of corrosion in grounding systems, which are differentiated by their requirements in terms of electrical performance, apart from their acceptable behaviour against aggressive agents of the terrain.

The purpose of this work is to analyse the influence of soil characteristics and humidity on the morphology and properties defined for grounding electrodes. The decomposition rates were established by electrochemical techniques using potentiodynamic curves and linear polarization resistance measurements [16].

2. Methodology
For this work two types of soils characteristic of the city of Tunja, Colombia were referenced, as Guerrero et al. [5], where a single level of humidity was used. The matrix of the experimental design was defined with two types of soil: sandy and clay loam, two electrode materials and 7 different levels of humidity, to make an adequate sweep in each experimental treatment.

The soil samples were taken to the respective analysis laboratory at the “Universidad Pedagógica y Tecnológica de Colombia (UPTC)” to obtain data such as: texture, pH, percentage of organic material, phosphorus, aluminium, potassium, calcium, magnesium, cation exchange capacity and characterization of electrical conductivity for these two types of soil [5]. The electrolyte used in the cell was obtained from soil samples prepared with the 7 moisture levels, from 10 to 40%.

According to the respective table consulted in the Electrical Installations Regiment RETIE [1], IEEE Standards [11, 13-14] and ICONTEC Guide [15], the test electrodes were chosen: copper and stainless steel. These electrodes are most commonly used in earthing systems [12].

The experimental matrix considers three factors (Table 1): soil type, with two levels: sandy loam and clay loam; Electrode material, with two levels: copper and stainless steel, and humidity, with seven levels: from 10 to 40% humidity.

| Soil Factor   | Electrodes       | Humidity Factor | FH |
|---------------|------------------|-----------------|----|
| Sandy Loam    | Copper           | 10%             | 10 |
| Clay Loam     | Stainless Steel  | 15%             | 15 |
|               |                  | 20%             | 20 |
|               |                  | 25%             | 25 |
|               |                  | 30%             | 30 |
|               |                  | 35%             | 35 |
|               |                  | 40%             | 40 |

Potentiodynamic curves were used to obtain an accurate estimate of the corrosion rate of the metal in the solution with the soil. The current is measured in the cell with a potential sweep and is presented in logarithmic scale. The potential sweep was made from about 500mV to its open circuit potential.

3. Results and discussion

3.1. Potentiodynamic curves
The graphs obtained for each electrode system and terrain are detailed in the following Figures 1 and 2.

If the Tafel approximation is used, for the copper electrode in the experimental arrangements with the two types of soil, it is observed that as the moisture increases the corrosion rate shifts to the right less than a decade. For moisture values greater than 30% no significant variations in rate and corrosion potential are observed.
Figure 1. Potentiodynamic curves for Copper electrode in clay and sandy loam soil with variation in moisture.

Figure 2. Potentiodynamic curves for Stainless Steel electrode in clay and sandy loam soil with variation in moisture.

The potentiodynamic curves for stainless steel present the typical asymmetry between the anodic branch and the cathodic branch, because the anodic branch presents an infinite slope. The Tafel approximation will be calculated with a few points close to the corrosion potential. The behaviour of the steel for the two arrangements, visually, presents little variation.

3.2. Summary of results
The results obtained after the Tafel approximation for each treatment can be synthesized in Tables 2 and 3.

| Humidity % | E corr (mV) | I corr (µA/cm²) | CR (mm/yr) | E corr (mV) | I corr (µA/cm²) | CR (mm/yr) |
|-----------|------------|----------------|------------|------------|----------------|------------|
| 10        | -104.4     | 31.27          | 0.3622     | -63.63     | 55.62          | 0.6443     |
| 15        | -113.3     | 49.86          | 0.5776     | -97.77     | 56.45          | 0.6548     |
| 20        | -121.2     | 60.79          | 0.7042     | -118.4     | 215.4          | 2.495      |
| 25        | -130.4     | 60.66          | 0.7026     | -136.0     | 331.2          | 3.837      |
| 30        | -235.9     | 62.51          | 0.7241     | -179.9     | 428.1          | 4.960      |
| 35        | -236.2     | 62.69          | 0.7261     | -201.1     | 458.7          | 5.313      |
| 40        | -236.3     | 62.82          | 0.7277     | -211.3     | 460.2          | 5.331      |
Table 3. Synthesis of results of electrochemical tests in the stainless.

| Humidity % | Stainless Clay Loam | Stainless steel - Sandy Loam |
|------------|---------------------|-----------------------------|
|            | E corr (mV) | I corr (µA/cm²) | CR (mm/yr) | E corr (mV) | I corr (µA/cm²) | CR (mm/yr) |
| 10         | -119.8       | 10.50            | 0.1217     | -98.34      | 17.72           | 0.2052     |
| 15         | -142.6       | 10.98            | 0.1272     | -123.4      | 27.91           | 0.3233     |
| 20         | -181.3       | 13.48            | 0.1561     | -177.5      | 33.38           | 0.3867     |
| 25         | -216.7       | 15.94            | 0.1846     | -202.1      | 33.24           | 0.3850     |
| 30         | -250.3       | 28.06            | 0.3250     | -266.0      | 36.08           | 0.4179     |
| 35         | -274.8       | 30.17            | 0.3495     | -247.7      | 37.70           | 0.4368     |
| 40         | -281.2       | 32.11            | 0.3739     | -251.7      | 39.50           | 0.4576     |

3.3. Discussion

In the copper electrodes, when comparing the Tafel slopes, a control is verified by transfer of load and mass, fact that is evidenced more clearly when registering rates of corrosion always greater than the stainless steel. Although the remarkable increase in the corrosion rate for the copper-free arrangement must present an additional mechanism.

In Figure 2, potentiodynamic curves of the stainless steel for the different arrangements, present a zone in the anodic branch where the current becomes constant, evidence of the control mechanism of corrosion by diffusion.

Figure 3 show the corrosion rates for copper and stainless steel in the two experimental areas. As expected, the rates for copper are comparatively higher than those of stainless steel in the two soils, which is explained by their conductivity that facilitates ionic mobility.

The corrosion rate values for a copper electrode in the sandy loam soil are significantly higher than the other soil-electrode combinations. There is no concrete explanation for this phenomenon, because errors were ruled out in the experimental procedure following the replicate protocol in the treatments.

![Copper Electrode](Image)

![Stainless Steel Electrode](Image)

Figure 3. Comparison of corrosion rate for experimental samples.

The behaviour for any soil regardless of the electrode used is similar qualitatively. The rate of corrosion undergoes large increases in moisture ranging from 10 to 20 or 25%, while for moistures over 30% tends to stabilize. This suggests that there is a limiting corrosion rate for a particular type of soil with the highest possible moisture.

3.4. Mathematical model

The behaviour of the corrosion rate as a function of humidity has a noticeable tendency in the data obtained in the laboratory for the potentiodynamic curves. The moisture is deduced as a fundamental factor in the phenomenon of metals corrosion buried in the soil because it determines the base environment of the electrolyte for the conduction of dissociated ions in the water. At higher humidity, a tendency of increase in the speed of corrosion is obvious. However, this trend is not linear. A final
corrosion value is observed at the asymptotically tended by this rat as the moisture is increased. It is
induced that the ion exchange between the electrolyte and dry soil should be zero. Therefore, we are
looking for a model that replicates this functional dependency.

The solution of the first-order differential equation deduced for this phenomenon would be:

\[ C \cdot R = C \cdot R \cdot F \left(1 - e^{-\frac{h}{\rho}}\right) \]  

That determines the behaviour of C.R. (corrosion rate) In terms of \( h \) (soil moisture %). C.R.F. is
called final corrosion rate. And \( \rho \) is a factor arising from proportionality with the same units as the
humidity (percentage) and that would involve soil properties and instant humidity. In a more complete
model this value must include factors such as soil permeability to moisture and electrode reactive ions
and that are present in the soil.

The regression that can be implemented for the experiments with variation of humidity arise from
the clearance of \( h \) as a function of C.R (equation 2). The behaviour of C.R. Depending on the factor is
detailed in Figure 4.

\[ h = -\rho \cdot \ln \left(1 - \frac{C \cdot R}{C \cdot R \cdot F}\right) \]  

![Figure 4](imageURL)

4. Conclusions
Corrosion rates were established for the different experimental arrangements, the behaviour of the
copper electrode standing out when interacting with the sandy loam soil, experimental samples that
yielded very different results to the other arrangements.

A marked difference between the rate of corrosion when measured for copper or for steel was
observed. The mechanisms in which these elements control corrosion is very different: while in steel
there is control by diffusion, in copper it is made by transfer of mass and charge. The Franco-sandy floor
was the most aggressive against metal electrodes.

The level of humidity plays a leading role in the phenomenon of corrosion of buried structures.
However, the variability of terrain when exposed to the weather did not allow precise and rapid
measurements of the corrosion rate, a problem that solves the electrochemical techniques allowing the
generation of rapid and controlled responses to influential factors.
The generated mathematical model faithfully explains the phenomenon of change of C.R. as a function of moisture. However, it is still necessary to find the relation between the factor defined in the model and the precise characteristics of the soil, such as the permeability or the quantity of ions present in the soil.

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