Characteristics of the electro resistivity of a compacted iron ore tailing

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ABSTRACT

The new legislation in Brazil has brought more attention to the technique of stacking filtered iron ore tailings for mining waste disposal. To minimize the risk of liquefaction, it's important to maintain the compacted structure in an unsaturated condition. This requires knowledge of the hydraulic characteristics of the material in order to evaluate the long-term performance of the embankment and design an adequate monitoring system. One way to track the material's behavior in the field is through electrical resistivity techniques. Using an electrical resistivity measurement system at various frequencies and current levels, we evaluated the behaviour of compacted iron ore waste. The examined tailings have been deposited in filtered tailings piles, which are intended to exceed a height of 100 meters. This study aims to investigate the electrical response of the material to different levels of water content, degree of saturation and suction. It was possible to establish good correlations between electrical resistivity and factors such as suction, degree of saturation, and water content. It was also identified an association between the electrical resistivity and the optimum water content.

Keywords: Electroresistivity, Iron ore tailing, Unsaturated material

1. Introduction

Despite presenting itself as an environmentally more advantageous option, dry stacking requires studies on the material's behavior under different saturation conditions. The deposition process of the filtered tailings occurs through compaction, carried out in the unsaturated condition, utilizing a specific compaction energy. However, throughout its lifespan, the stack may experience infiltrations due to precipitation or capillarity, which could eventually lead to saturation at certain points in the embankment. Given that the risk of failure is higher in the saturated state or near this condition, monitoring saturation becomes imperative. Several authors have discussed the behavior of filtered tailings landfills, focusing on seasonal water movement throughout the depth, and emphasizing the importance of maintaining low saturation levels (e.g. Lupo and Hall, 2010; Amoah et al. 2018; Oldecop and Rodari, 2021).

Considering that these stacks can exceed heights of 100 meters, implementing monitoring systems can be challenging. A straightforward option would be the installation of cables with electrodes for monitoring through electro resistivity. This study is part of a research project funded by Vale S.A to investigate the water retention capacity of compacted filtered tailings. The study utilizes water content and suction sensors for comparison with the electro resistivity method. The focus of this study is to assess a more practical and efficient method for monitoring the flow pattern in compacted tailings stacks. The current paper presents the results obtained from compacted specimens subjected to various water content conditions and degrees of saturation, with the electrical resistance of the material being measured.

2. Methods and Material

2.1. The iron ore tailing

The tailings used in the study correspond to the flotation tailings material derived from iron ore extraction at the Pico's Mine, located in the municipality of Itabirito, in the state of Minas Gerais. This mine is operated by Vale S.A. The mineralogical characterization of the tailings was conducted using X-ray diffraction (XRD) analysis. The data from the XRD analysis identified the different mineral phases present in the flotation tailings used in this study. This tailings material is predominantly composed of quartz and hematite, with quartz accounting for 89.1% of the total composition of the tailings.

From a granulometric perspective, the material is classified as silt (80%), with approximately 3% of the grains being clay sized. The material exhibits non-plastic behavior; hence no significant volume change is expected during the drying process. Figure 1 illustrates the compaction curve (standard Proctor energy) and the initial compaction conditions of the tested specimens. The values for maximum dry density and optimum water content were 2.015 g/cm³ and 11.9%, respectively.

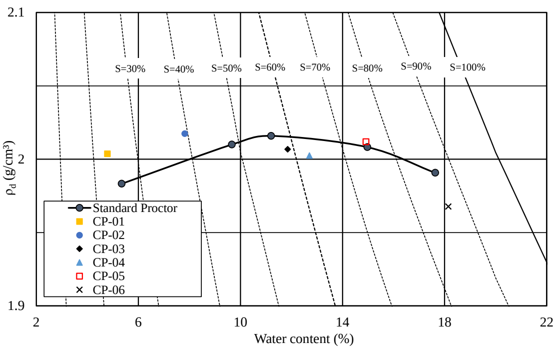

Figure 1. Compaction curve and position of compacted specimens

Each specimen was statically compacted in a PVC mold with a diameter of 44 mm and a height of 99 mm. The compaction aimed to achieve a compaction degree of 100% for six different water contents. As observed in Figure 1, there was a slight variation in the achieved densities, but it is considered that this aspect should not affect the analyses.

The as compacted characteristics of each specimen are presented in Table 1. After compaction, initial suction was obtained, and the electrical resistance of each specimen was measured using three currents, as described in the following section. Following the initial measurement, each specimen underwent water loss through evaporation at room temperature to induce a decrease in water content and degree of saturation, as well as an increase in suction. The suctions were obtained using the filter paper method, following the recommendations of Chandler et al. (1992) and Marinho and Oliveira (2006), which involved the use of sacrificial filter paper to prevent contamination by the material.

Table 1. Initial conditions of the specimens tested.

Specimen	w (%)	e	S (%)	Suction$_i$ (kPa)
1	4.54	0.63	24	70
2	7.54	0.63	40	53
3	11.59	0.65	60	41
4	12.4	0.66	63	31
5	14.67	0.65	76	21
6	17.79	0.75	79	11

2.2. The experiment

After determining the suction and weighing the specimens for subsequent calculations of water content and degree of saturation, electrodes were introduced to conduct resistivity measurements. Figure 2 illustrates the test execution and the electrode positions.

The readings of resistivity values were performed using the Terrameter SAS 300B resistivity meter. The method involves injecting an electric current into the soil through electrodes and measuring the resulting voltage. Three different electric current values were employed (0.2, 0.5, and 1.0 mA). Thus, each specimen had its electrical resistivity determined with these three currents for each suction, water content, and degree of saturation.

The experimental setup for the study is similar to that utilized by Ya et al. (2017) and Chu et al. (2018). Figure 2a shows a photo of one of the ongoing tests, and Figure 2b illustrates the adopted electrical system.

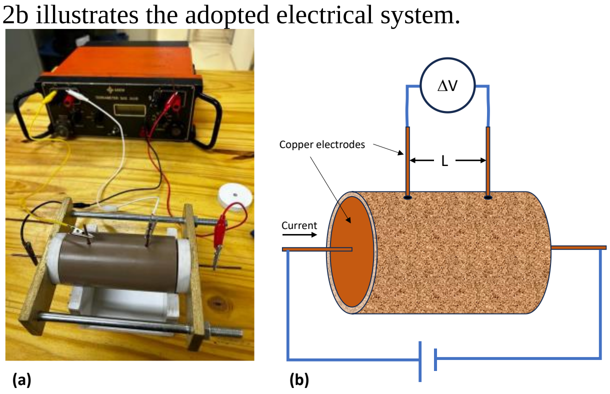

Figure 2. Test Execution and Electrode Position Illustration.

The calculations for determining electrical resistance are based on Ohm's Law, Eq (1):

$$R = \frac{\Delta V}{I} \quad (1)$$

where (R) is the electrical resistance, ΔV is the potential difference, and I is the electric current.

The electrical resistivity (ρ) is given by Eq. (2), allowing the determination of R based on the obtained reading:

$$\rho = \frac{RA}{L} \quad (2)$$

where A is the cross-sectional area and L is the distance between electrodes.

3. Results and discussion

3.1. The SWRC

In Figure 3, the soil water retention curve (SWRC) for the iron ore tailings used in this study is presented. The points depicted in the Figure represent all measured values for each specimen in the as-compacted condition and after the two drying stages. These values are presented alongside the curve fit determined for the material. The fitting process utilized data (not presented in this study) obtained through various suction measurement methods, including the filter paper method. It is observed that the data obtained for the specimens in this study align well with the general curve. However, a slight variation is noted for higher suction values.

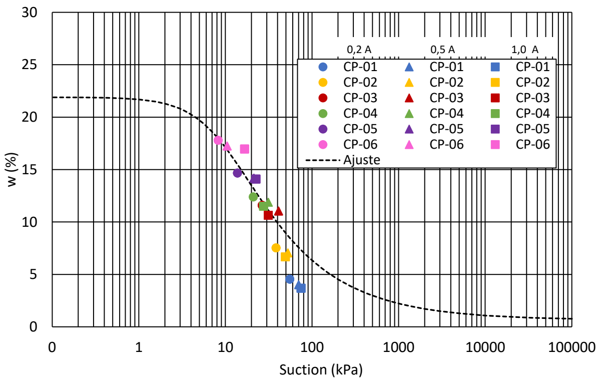

Figure 3. Soil water retention curve

3.2. Resistivity

The variation of material electric resistance with water content is depicted in Figure 4. Also indicated in Figure 4 is an adjustment and equation considering all the collected data. It is emphasized that this adjustment is valid for a void index of the same order as the one that was used. The variations in symbols used in the graphical representation serve to identify the points obtained with three different applied currents, namely: 0.2 A, 0.5 A, and 1 A. A notable sensitivity of resistance to water content is observed for values below approximately 11% (167 Ω/%), coinciding with the optimum water content obtained. For water content values exceeding 11%, the sensitivity of resistance is significantly reduced (21 Ω/%). Similar results were also obtained by Zha et al. (2006) in specimens of compacted expansive soil.

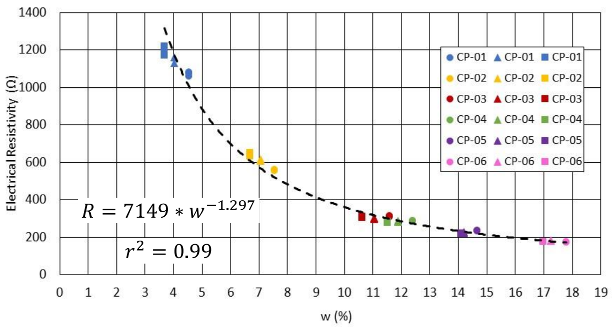

Figure 4. Relation between electrical resistivity and water content for different currents applied.

A very similar behavior is observed in the relationship between electrical resistance and the degree of saturation, which also exhibits the same point of reduced sensitivity at a degree of saturation of approximately 60%, as shown in Figure 5. Figure 5 also presents an adjustment and equation considering all the collected data. Yan et al. (2012) demonstrated a similar behavior in compacted expansive soil.

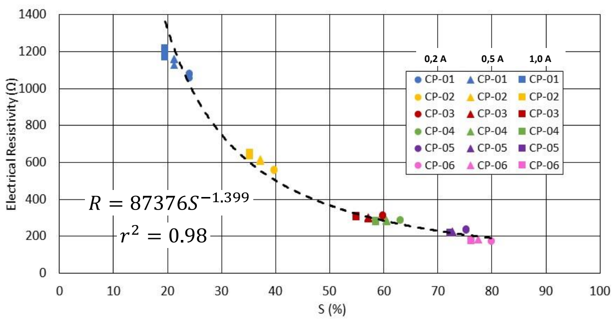

Figure 5. Relation between electrical resistivity and degree of saturation for different currents applied.

In Figure 6, the relationship between electrical resistance and suction is presented. An adjustment equation for the tested material is also provided. showing a similar pattern as in the previous comparisons with a distinct point of sensitivity change between resistance and suction. However, the change is less pronounced. A similar trend was observed by Yan et al. (2012).

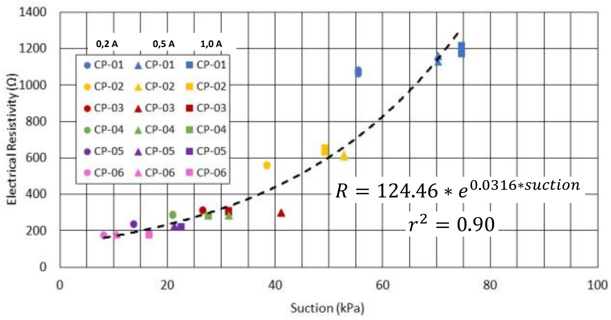

Figure 6. Relation between electrical resistivity and suction for different currents applied.

The equations obtained for each of the correlations presented earlier are shown in Table 2..

Table 2. Equations obtained and their respective r^2

	Equation	r^2
Water content	$R = 7149 * w^{-1.297}$	0.99
Degree of saturation	$R = 87376 * S^{-1.399}$	0.98
Suction	$R = 124.46e^{0.0316*suction}$	0.90

In Figures 3 and 4, it is not clearly discernible whether there is any effect of the induced current on the obtained results. However, upon careful evaluation of the data, a slight variation is detected for the more humid samples. Figure 7a illustrates the variation of electrical resistance with applied current. To emphasize the effect, only the data from the driest and most humid samples were plotted. It is observed that besides a difference between the wet and dry branches, a slight variation in resistance with the change in current was noticed in the samples from the dry branch. In wet branch samples, variations in electrical resistivity are not discernible on the scale used. To better correlate with water content, Figure 7B presents the water content values of the samples used in this analysis.

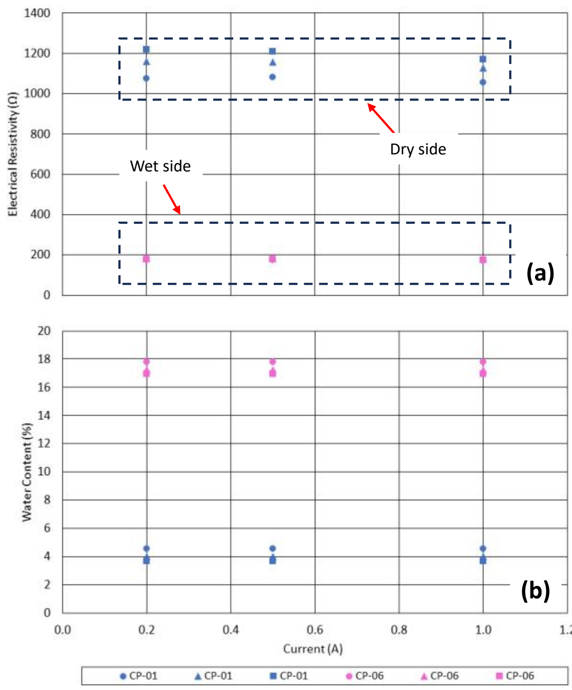

Figure 7. Electrical resistivity according to the imposed current indicating the effect of the water content.

4. Conclusions

The study involved compacted iron ore tailings, utilizing a TERRAMETER SAS 300 B resistivity meter to measure the electrical resistivity of the specimens. The results demonstrated a strong correlation between electrical resistance and both water content and the degree of saturation and suction for the iron ore tailing tested. Detection of suction variations appears to be more effective than variations in water content. An interesting aspect of the obtained results is the correlation between the alteration in the relationships between change in suction and degree of saturation with electrical resistivity. The minimum radius points in the curves adjusted to the data indicate that this change in behavior occurs very close to the optimal water content of the standard Proctor compaction test. For suction values less than approximately 30 kPa, the rate of variation is 7 Ω/kPa, while for suction values above this threshold, the variation increases to 21 Ω/kPa. A similar behavior is observed with the degree of saturation. For degree of saturation higher than approximately 60% (an approximate value at the inflection point), electrical resistivity becomes less sensitive to increased saturation degree.

It was observed that the applied currents (0.5 and 1 A) did not induce significant changes in the measured values for drier materials and induced a not important variation for wet material. In conclusion, resistivity measurement proves valuable for understanding water distribution and movement in filtered tailings stacks. Further studies with larger variations in density and suction are anticipated to enhance our understanding of the method's application in measuring water content, degree of saturation, and suction.

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