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Experimental study on Soil-Water Characteristic Curves (SWCC) for fine grained soils and mine tailings

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ABSTRACT: The Soil–Water Characteristic Curve (SWCC) is a fundamental function for understanding the engineering behavior of unsaturated natural soils or mine tailings. The SWCC defines the relationship between water content and matric suction and plays an important role in prediction of unsaturated soil properties, such as hydraulic conductivity or shear strength. In this study, an experimental program was conducted to determine the SWCC and its main parameters, for which laboratory tests were carried out on 60 samples, including natural soils and mine tailings. The axis translation technique was applied, using Tempe cells and the pressure extractor plate equipment. The effects of soil basic characteristics such as fines content, plasticity and density on the SWCC were investigated, and a SWCC estimation method is proposed based on this characterization. The findings of this research highlight the trend of the SWCC depending on different soil characteristics, and these trends are also in good agreement with the literature. Finally, the estimation method provides a valuable reference for understanding and choosing SWCC parameters for design purposes, both in fine grained soils and mine tailings.

KEYWORDS: SWCC, suction, soils, tailings

1 INTRODUCTION

In contrast to saturated soils, which are widely studied in geotechnical engineering and ideally contain solid and liquid phases, unsaturated soils are characterized by additionally having the gaseous phase, with the interaction between the liquid and gaseous phases, and consequent generation of negative interstitial tension or suction (Fredlund et al., 2012). The Soil-Water Characteristic Curve (SWCC) provides a conceptual understanding of the relationship between the mass (and/or volume) of the liquid phase (or water) and the state of suction in a soil.

The SWCC has proven to be an interpretive model that utilizes the elementary capillary model to provide insights into the distribution of water within soil pores. It plays a crucial role in determining the properties of unsaturated soils, such as hydraulic conductivity, shear strength, and volumetric change under unsaturated conditions, which are a function of suction. The procedures proposed for determining these functions based on the SWCC are approximate, but they have demonstrated satisfactory performance for analyzing problems involving unsaturated soils. As a result, SWCCs are considered key to implementing unsaturated soil mechanics in geotechnical engineering practice.

The mining industry is one of the fields of application of properties of unsaturated soils, in which it is required to understand and provide engineering solutions to phenomena such as unsaturated flow and infiltration, shear strength and volume change, in natural soils and mine tailings. Mine tailings are materials present in large quantities in mining operations, which in recent years tend to be managed in an unsaturated state for safety and regulatory reasons (e.g. GISTM, 2020). Therefore, the determination of SWCC emerges as a key element to characterize these materials to perform a more comprehensive geotechnical evaluation.

In this context, this study presents the results of various SWCC laboratory tests on soils and tailings samples, as well as their main fitting parameters. In addition, the influence of standard geotechnical characteristics on the SWCC and a SWCC estimation method are presented.

2 SOIL-WATER CHARACTERISTIC CURVE (SWCC)

The SWCC is expressed as the graphical representation of the relationship between water content, whether gravimetric, volumetric or degree of saturation, and soil suction. This relationship also represents the water storage capacity of a soil at different suction states, which can be either matric suction or total suction.

There are two points of the SWCC that deserve special attention and divide it into three zones (see Figure 1). The first point corresponds to the air-entry value (AEV) which represents the value of suction necessary to cause the highest pore drainage of the soil and consequently its desaturation. The other is associated with the beginning of the residual stage of soil desaturation, where the effect of suction to cause additional water loss decreases and water removal requires steam flow.

Vanapalli et al. (1999) point out that soil characteristics influence SWCC. Factors such as soil type, density, mineralogy, or initial moisture content (wetting or drying path) also have an effect on the SWCC. Soil particle size distribution is also a factor affecting the suction-to-wetting ratio. Typically, the higher the number of fine particles (clays) the higher the moisture content for the same suction (Fredlund & Rahardjo, 1993). The influence of some of these factors is discussed in the present work.

There are several techniques for measuring SWCC, which vary widely in terms of cost, complexity and measurement range. Soil suction can vary in the range of 0 to 1000000 kPa and this is the main reason why there are numerous techniques for its determination.

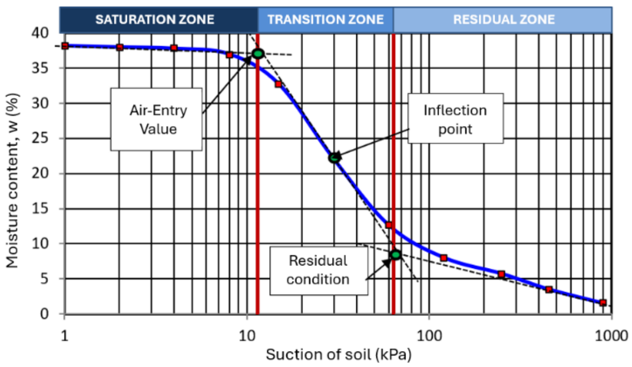

Figure 1. Typical soil-water characteristics curve and its zoning.

Experimental techniques for SWCC determination are generally classified as laboratory methods and field methods and they are differentiated by the component of the suction (matric or total) that is measured. In addition, these are also differentiated as direct and indirect methods. Direct methods measure negative water pressure in the soil pores or control the pressures of water and air in the pores to obtain suction. Indirect methods determine suction based on the moisture equilibrium condition of the soil, with measurements of vapor pressure, moisture content or physical properties (thermal or electrical conductivity) of a porous medium in equilibrium with the soil.

Figure 2 summarizes the main experimental techniques and shows the approximate ranges of application where the various techniques are practical. In the present work, the axis translation technique is applied (Lu & Likos, 2004), using Tempe cells and a pressure extractor plate in the laboratory.

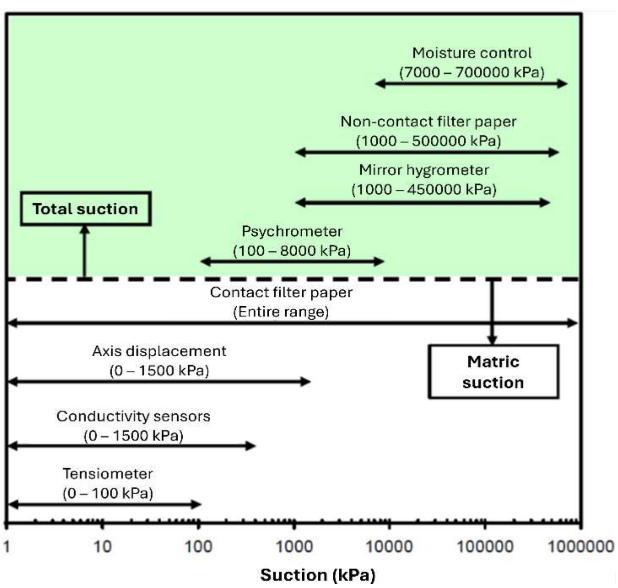

Figure 2. SWCC measurement techniques (Lu & Likos, 2004).

3 EXPERIMENTAL PROGRAM

The experimental program was designed considering the research objectives. The main objective was to measure the SWCC of the materials under study (natural soils and tailings), which will then allow studying the influence of certain characteristics of the materials on the results. The experimental program included different types of tests. A basic characterization was carried out first, and then the pressure cell tests using the axis translation technique were carried out to obtain the SWCC.

The equipment used for the tests were the Tempe cells, with a suction measurement capacity of up to 500 kPa, and the pressure extractor plate, with a capacity of up to 1500 kPa. All laboratory tests were carried out at the WSP Peru laboratory, and the test procedures are based on ASTM standards and in-house protocols. The experimental program is summarized below.

3.1 *Geotechnical characterization*

Sixty different samples were tested, of which 18 were soil samples and 42 were tailings samples. Their physical properties, such as particle size, consistency limits and plasticity index (PI), and solids specific gravity (Gs) were investigated. The Unified Soil Classification System (USCS) was used for soil classification. The ranges of the physical properties of the tested materials are summarized by in Table 1.

Table 1. Summary of soils and tailings standard properties.

Material	*USCS*	*Gs*	*PI*	*Fines(%)*
Soil	SM	2.59 – 2.69	NP – 21	14 – 39
	SC	2.72 – 2.81	13 – 19	30 – 43
	ML	2.85	NP	74
	MH	2.74	23	51
	CL	2.72 – 2.78	9 – 16	50 – 76
	CH	2.62 – 2.75	36 – 61	77 – 80
Tailings	SM	2.68 – 3.78	NP	0 – 49
	ML	2.68 – 3.34	NP	57 – 92
	CL-ML	3.86	NP	98
	CL	2.90 – 3.24	7 – 14	60 – 93

3.2 *Tempe cell tests*

The Tempe cell consists of a cylindrical chamber of acrylic material, with an internal diameter and height of approximately 7 cm, plus a base and top cover (see Figure 3). The Tempe cell is designed to work with pressures up to 500 kPa.

The base of the Tempe cell contains the water drainage system, which is in direct contact with a high air-entry value ceramic disc. The lid contains an air-entry pressure duct, which will allow a controlled supply of pressurized air from a pressure panel. The water that reaches the drainage spiral is connected to the atmosphere through an outlet duct; and thus, the air pressure entering the cell and the water pressure at the base are separated across the air-water interfaces of the saturated pores of the ceramic disk (principle of axis translation).

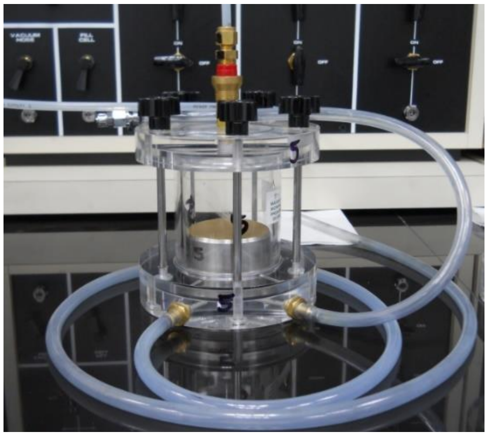

Figure 3. SWCC test with Tempe cell.

The test procedure, in brief, comprises the following steps:

i. Preparation of test specimens.
ii. Saturation of the ceramic disc and test specimen.
iii. Cell configuration and installation on the pressure panel.
iv. Application of air pressures and monitoring of the test (control of mass and pressure increments).
v. Recording of final specimen moisture content.

The suction imposed for the tests in this study are the typical values used for the Tempe cell: 1, 2, 4, 8, 8, 15, 30, 60, 60, 120, 250 and 500 kPa. Once the highest level was reached in each test, the cell was disassembled, and the final moisture content was calculated. This moisture content is used calculate the values corresponding to the previous matric suction levels (back-calculation), completing the suction and moisture pairs for each SWCC.

3.3 *Tests with pressure extractor plate*

The operating principle of the pressure extractor plate is the same as that of the Tempe cells and described above. The main components of the pressure extractor plate system are a metallic cell and a ceramic disc with a high air-entry value. Being a more robust and larger equipment (30 cm internal diameter), it supports higher pressures and therefore higher suction values. This equipment is applicable for suction ranges up to 1500 kPa, which corresponds to the highest air-entry value for a commercial ceramic disc. A detailed analysis of this method is provided by Bocking and Fredlund (1980). It should be noted that in the present work a maximum of 1000 kPa was considered, due to the prolonged time required for equilibrium during the application of a high level of suction.

On the other hand, the extractor plate has capacity for a larger number of specimens to be tested at the same time. The moisture measurement at each value of suction is made directly on the specimens, for which after each equilibrium is reached, the applied pressure is removed, and the pressure plate is opened to make the measurements. Figure 4 shows a view of some specimens in the pressure extractor plate tested for the present work.

Figure 4. Samples in SWCC test with pressure extractor plate.

The point cloud with the results of both tests, Tempe cell and pressure extractor plate, is shown in Figure 5. Results can be seen by type of material and USCS classification. The interpretation and analysis of these results are described in detail in the following section.

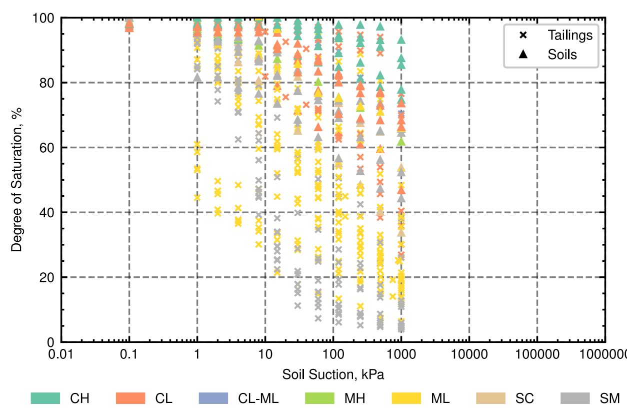

Figure 5. Point cloud of SWCC test results.

4 ANALYSIS OF RESULTS

After the experimental stage, the next step is to represent the SWCC as a continuous curve, so that it is feasible to use it in a numerical model or for the estimation of other property functions of unsaturated soils. A continuous function also allows a proper estimation of the AEV of each material.

For this, the experimental values, which are discrete points, are adjusted after each test by means of continuous mathematical equations. Among the equations proposed in the literature, those of van Genuchten (1980), Fredlund & Xing (1994), Pham & Fredlund (2011), stand out. The most widely used and implemented in engineering software is the one proposed by Fredlund & Xing (1994), which is presented below in equations 1 and 2:

$$S(\psi) = C(\psi)\frac{1}{\left\{\ln\left[e+\left(\psi/a_f\right)^{n_f}\right]\right\}^{m_f}} \tag{1}$$

$$C(\psi) = 1 - \frac{\ln(1+\psi/\psi_r)}{\ln[1+(10^6/\psi_r)]} \tag{2}$$

Where a_f is the adjustment parameter related to the air entry value, n_f is the adjustment parameter related to the rate of water loss once the air entry value is exceeded, m_f the adjustment parameter related to the residual moisture content and ψ_r the residual suction. In addition, S is the degree of saturation, ψ is the matric suction and e the Euler number (e = 2.7182).

Next, Figures 6 to 9 present the results of the SWCC adjusted by the Fredlund & Xing (1994) equation, showing their sensitivity to material type characteristics such as solids' specific gravity, plasticity index, fines content and test dry density.

Respect to specific gravity of solids, the values measured in the soil samples were generally less than 3, in contrast to the tailing's samples, where maximum values close to 4 were recorded for tailings coming from heavy minerals. The fitted SWCC, as presented in Figure 6, show no clear pattern of Gs influence on the results for both soils and tailings tested.

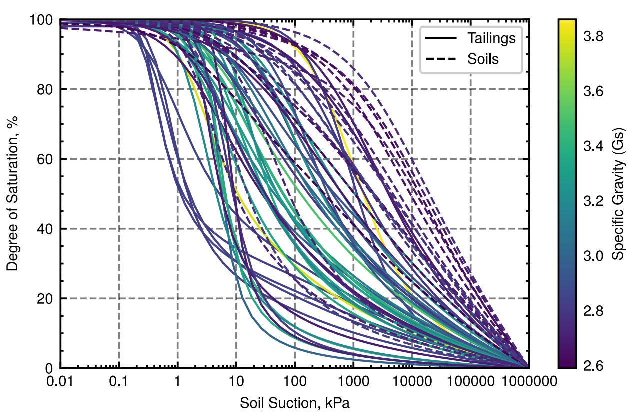

Figure 6. Adjusted SWCC and sensitivity to Gs.

On the other hand, Figure 7 shows a marked influence of the fines content on the SWCC. It can be noted that in general, the lower the fines content, as in the case of sandy soils, with less than 50% of fines, the SWCC tends to desaturate faster and consequently a lower AEV is obtained. The opposite occurs for samples with a fines content higher than 50%, as is the cases of silts and clays, where there is a higher suction demand for a given moisture content and consequently the SWCC falls slower, resulting in a higher AEV.

Something similar occurs with respect to the influence of the plasticity index. As can be seen in Figure 8, samples that do not present plasticity (NP), such as tailings, typically have a more pronounced break in SWCC at lower suction values, i.e. lower AEV. On the contrary, those with higher PI, more common in soil samples, retain more water and the AEVs are higher.

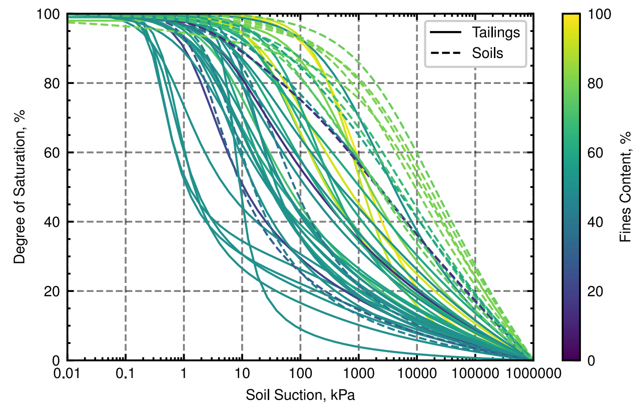

Figure 7. Adjusted SWCC and sensitivity to fines content.

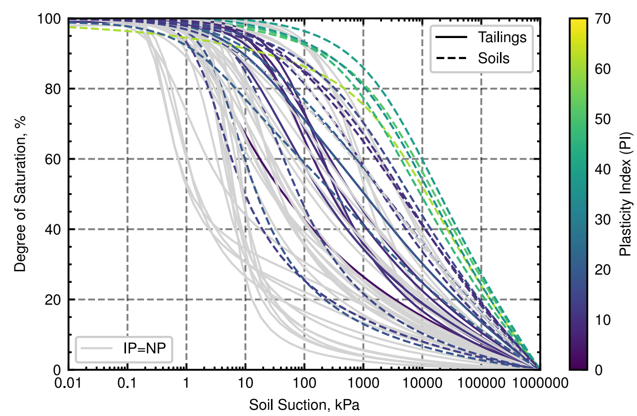

Figure 8. Adjusted SWCC and sensibility to PI.

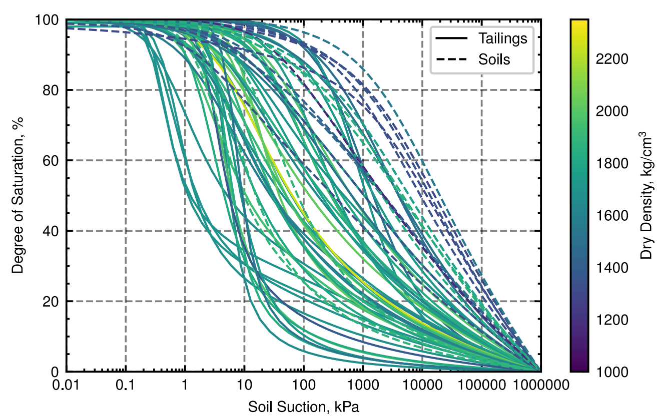

Figure 9. Adjusted SWCC and sensitivity to dry density.

According to Figure 9, a no definite pattern is seen with respect to the influence of the initial dry density of the test on the SWCC obtained; however, it should be noted that, in cases of fine soils with a tendency to volumetric change, the density is corrected since it has an influence on the volumetric calculations, including the degree of saturation. A shrinkage curve test is usually performed to support the SWCC tests (Fredlund et al, 2012).

5 SWCC ESTIMATION MODEL

Several SWCC predictive methods exist in the literature, mainly based on statistical and regression approaches. Sleep (2011) classified these methods into four approaches: an statistical approach as presented by Aubertin et al. (2003), a regression approach as presented by Zapata et al. (2000), a physical model approach as presented by Fredlund et al. (2002) and a approach using artificial intelligence as presented by Johari et al. (2006).

As a complement to the experimental results and the mathematical adjustment of the SWCC, a simplified estimation method based on correlations with basic characteristics commonly measured in the laboratory for both natural soils and mine tailings is proposed in this section. The regression approach has been used to correlate the SWCC parameters, specifically from the Fredlund & Xing (1994) fitting model, with the material type characteristics studied in the previous section. The most influential characteristics were analyzed, being able to verify that the SWCC is conditioned to a greater extent on the plasticity of the material (PI) and the fines content (CF), the latter being the one with the highest incidence.

The variation of the SWCC parameters was fitted by polynomial and exponential functions. Figure 10 shows the experimental correlation between these parameters and the CF in percentage.

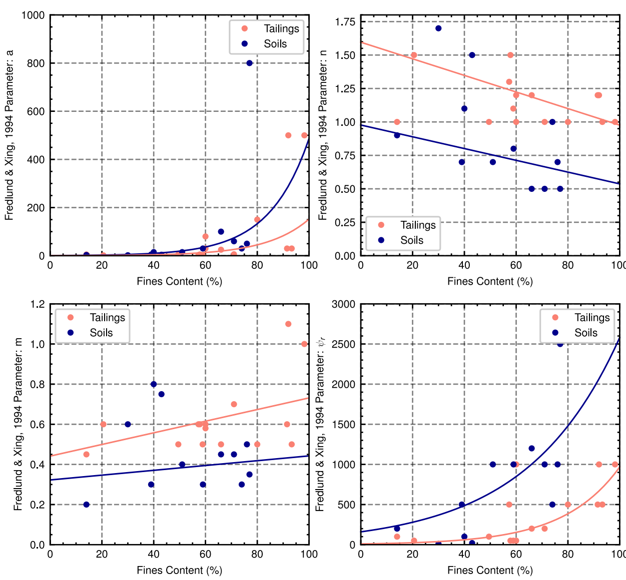

Figure 10 Correlation of experimental data with SWCC parameters from Fredlund & Xing (1994).

Based on the findings, a simple method for estimating the SWCC for both natural soils (sands with fines content or fine natural soils) and tailings is proposed by means of equations 3 to 10.

SWCC parameters for natural soils:

$$a = 0.738e^{0.065(CF)} \tag{3}$$
$$n = 0.977 - 0.0044(CF) \tag{4}$$
$$m = 0.323 + 0.0012(CF) \tag{5}$$
$$\psi_r = 160e^{0.028(CF)} \tag{6}$$

SWCC parameters for tailings:

$$a = 0.351e^{0.061(CF)} \tag{7}$$
$$n = 1.596 - 0.0062(CF) \tag{8}$$
$$m = 0.441 + 0.0029(CF) \tag{9}$$
$$\psi_r = 9.72e^{0.046(CF)} \tag{10}$$

Figures 11 and 12 show SWCC estimated by the method presented in this paper, for natural soils and mine tailings, respectively, which vary as a function of CF. This method represents a practical tool for the estimation of SWCC for geotechnical purposes in general, highlighting its application in the mining industry, since the soils and tailings data used in this study comes from mining projects.

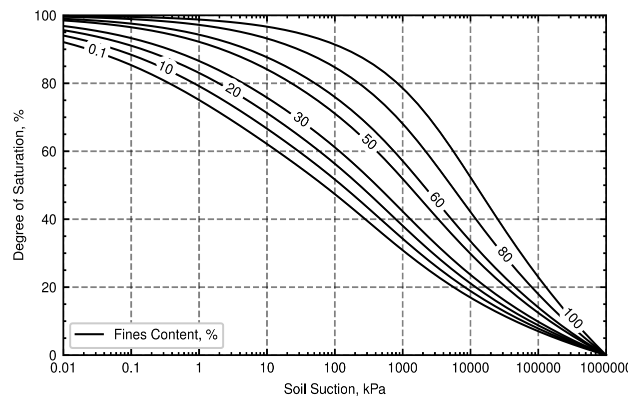

Figure 11. Estimated SWCC for natural soils.

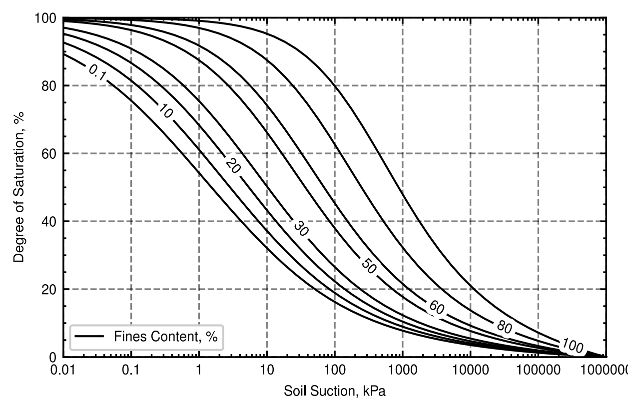

Figure 12. Estimated SWCC for tailings.

6 CONCLUSIONS

In the present study, soil-water characteristic curves (SWCC) were experimentally determined on a total of 60 samples, composed of 18 samples of natural soils and 42 samples of mine tailings. Tests using Tempe cell and pressure extractor plate equipment, both applying the principle of axis translation for the imposition of suction, proved to be suitable for the measurement of SWCC in the range of 0 to 1000 kPa.

The experimental results were adjusted with the model of Fredlund & Xing (1994) and the influence on SWCC of different measured characteristics of the tested materials, both in soils and tailings, was analyzed. From this analysis it was possible to verify that the SWCC is conditioned to a greater extent by the plasticity of the material (IP) and the fines content (CF), the latter being the one with the highest incidence.

A SWCC estimation method is proposed from a basic characterization, by determining the parameters of the Fredlund & Xing (1994) model correlated with the CF, both for natural soils (sands with fines content or fine natural soils) and mine tailings. This SWCC estimation method represents a practical tool for initial study stages, and the SWCC parameters can be directly implemented in engineering software for analysis with unsaturated soils.

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