SWCC: Experimental results of copper tailings and spent ore

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ABSTRACT: Modelling flow into mining geotechnical structures, such as heap leach, spent ore dumps or a tailings storage facility, should consider the fact that constitutive materials may be found in an unsaturated regime. A fundamental parameter for doing this type of analysis is the soil-water characteristic curve (SWCC), however, its empirical determination is not frequent due to availability and time restrictions. The current state of practice consists in the determination of these curves through indirect estimations which are not necessarily meant to be applied on particular materials as those from mining process.

This article presents the results of an experimental study on SWCC determination for spent ore and tailing materials, comparing their results with different estimation methods. Given the inability of the estimations of reproducing the actual behavior of those materials, an alternative focus is proposed to experimentally determine the SWCC using only three measurements, saving time and testing costs.

1 INTRODUCTION

Geotechnical structures associated with mining works are generally in a state of partial saturation, so any study of infiltration or flow into them must consider aspects of the mechanics of unsaturated soils. The soil-water characteristic curve (SWCC), which defines the ability of the soil to retain or release water, plays a fundamental role in the performance of these analyzes, so that its determination is vital. Determining empirically the SWCC can take from few days to several months, depending on the material; Due this, and the scarce availability of equipment in laboratories of soil mechanics, estimates are usually used from more accessible parameters.

In the present study, the results of an experimental campaign for the determination of moisture retention curves through pressure plate tests of materials from different mines, in particular, tailings and spent ore - for which there is not enough information available in the literature. In addition, the predictive capacity of three different estimation methods was investigated and, finally, a methodology is proposed to determine the suction curve that allows a reduction of the times and resources associated with pressure plate tests, proposing appropriate execution parameters for each type of material studied.

2 SOIL WATER CHARACERISTIC CURVE (SWCC)

The moisture retention curve (SWCC) is a graphical representation of the mathematical relationship between suction within a soil with water content or degree of saturation [1]. Originally developed for soil studies in agriculture. The SWCC represents the water storage capacity of a material versus different states of matrix suction. This curve generally presents two strong slope changes, the first change being the air entry value (AEV), which represents the suction at which the soil passes from a saturated to a partially saturated state and is associated with negative pore pressure. The second slope change represents a state of equilibrium, which is associated with a residual moisture content. Fig. 1 shows the shape of a type curve. In the agricultural field it is common to carry out tests to determine the moisture content at two typical suction values of 30 kPa and 1500 kPa, which represent the field capacity and the permanent wilting point respectively. Fig. 1 shows the typical shape of sandy, silty and clayey soils

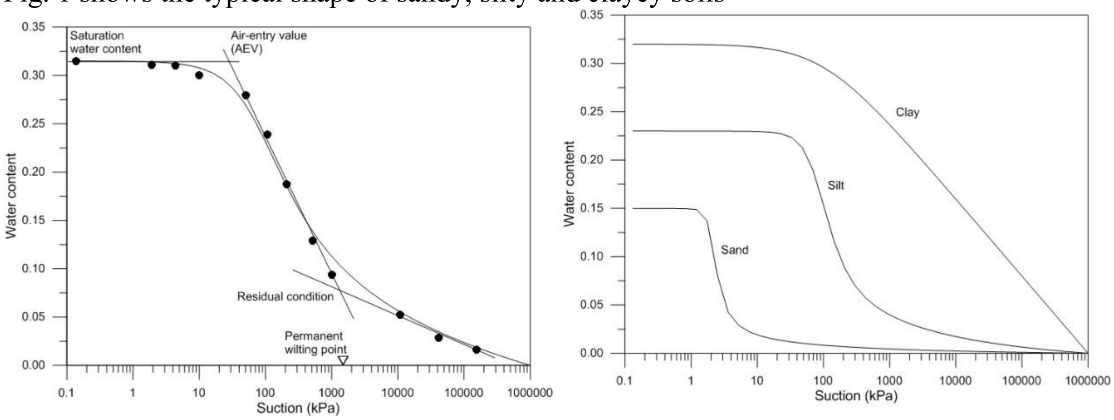

Figure 1. SWCC Example (Left). Typical Shape of sandy, silty and clayey soils (Right).

3 EMPIRICAL DETERMINATION SWCC CURVES

Empirical curves were determined from five samples from tailings storage facilities and nine from spent ore dumps, which originated from mining operations located in the north of Chile. The basic properties and particle size distributions of these materials are presented in Table 1 and, in Figs. 2 and 3, respectively.

Table 1. Properties of studied material.

Type	Name	γ_d (t/m^3)	Gs	e	n	d_{max} (mm)	% Gravel	% Sand	% Silt	% Clay
		(1)	(2)	(3)	(4)	(5)				
Tailing	Tailing 1	1.50	2.75	0.83	0.45	0.4	0	34	45	21
	Tailing 2	1.35	2.79	1.07	0.52	0.4	0	19	63	18
	Tailing 3	1.82	2.93	0.61	0.38	0.4	0	33	59	8
	Tailing 4	1.6	2.83	0.77	0.43	0.4	0	35	56	9
	Tailing 5	1.51	2.65	0.75	0.43	2	0	36	52	12
Spent ore	Spent ore 1	1.96	2.79	0.42	0.30	76.2	62	26	8	4
	Spent ore 2	1.84	2.79	0.52	0.34	25.4	55	30	12	3
	Spent ore 3	1.75	2.79	0.59	0.37	4.8	0	67	26	7
	Spent ore 4	1.60	2.79	0.74	0.43	4.8	0	67	26	7
	Spent ore 5	1.59	2.72	0.71	0.41	38.1	44	43	10	3
	Spent ore 6	1.50	2.66	0.77	0.44	50.8	56	28	11	5
	Spent ore 7	1.49	2.62	0.76	0.43	50.8	56	27	12	5
	Spent ore 8	1.46	2.66	0.82	0.45	38.1	56	26	14	4
	Spent ore 9	1.47	2.62	0.79	0.44	38.1	56	30	11	3

Note: (1) dry unit weight
(2) Specific gravity of soil solids
(3) Void ratio
(4) Porosity
(5) Maximum particle size

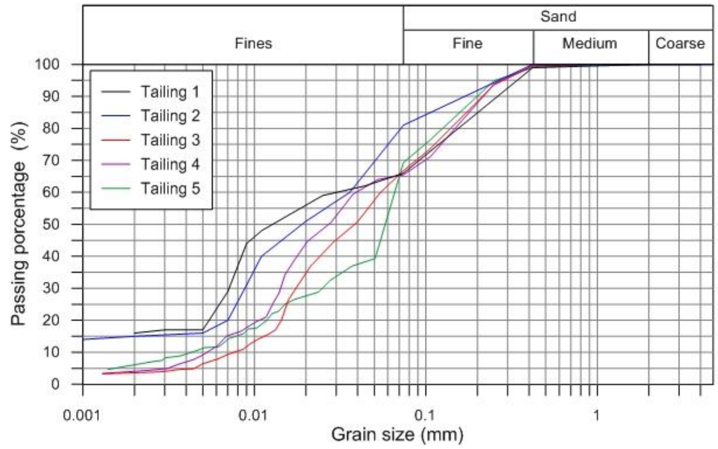

Figure 2. Particle size distribution of tailings.

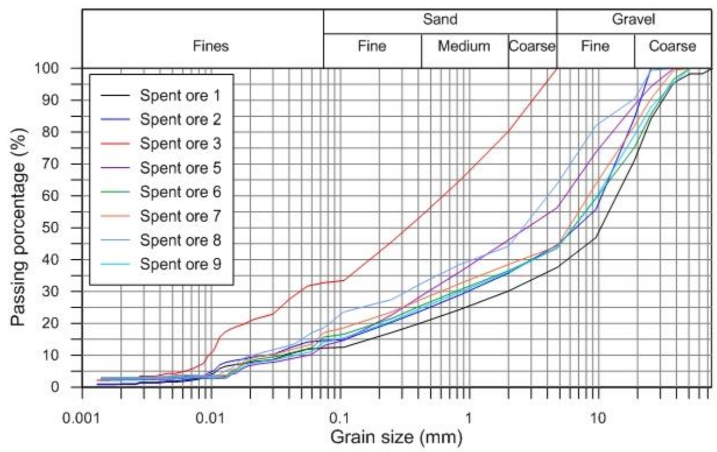

Figure 3. Particle size distribution of spent ore

Experimental determination of swcc was carried out using the pressure plate method [2], commonly used in Chile for agricultural studies (not so in soil mechanics laboratories). In this test saturated samples are placed inside a pressure chamber, then suction is applied until the sample removes retained water, reaching a state of equilibrium. Finally the gravimetric moisture content is determined by wet and dry mass difference.

In this study to construct the SWCC curve in the whole spectrum of possible suctions tests were executed at different suctions depending on the material. Fig. 4 shows samples and the equipment used in the execution of the test.

Figure 4. Pressure plate equipment used to obtain SWCC

Experimental results of the soils tested in the framework of this study can be observed in Fig. 5, below. It is possible to note the difference between results obtained for tailings with respect to spent ore, following the first the typical form of S, while latter have a relatively flat shape.

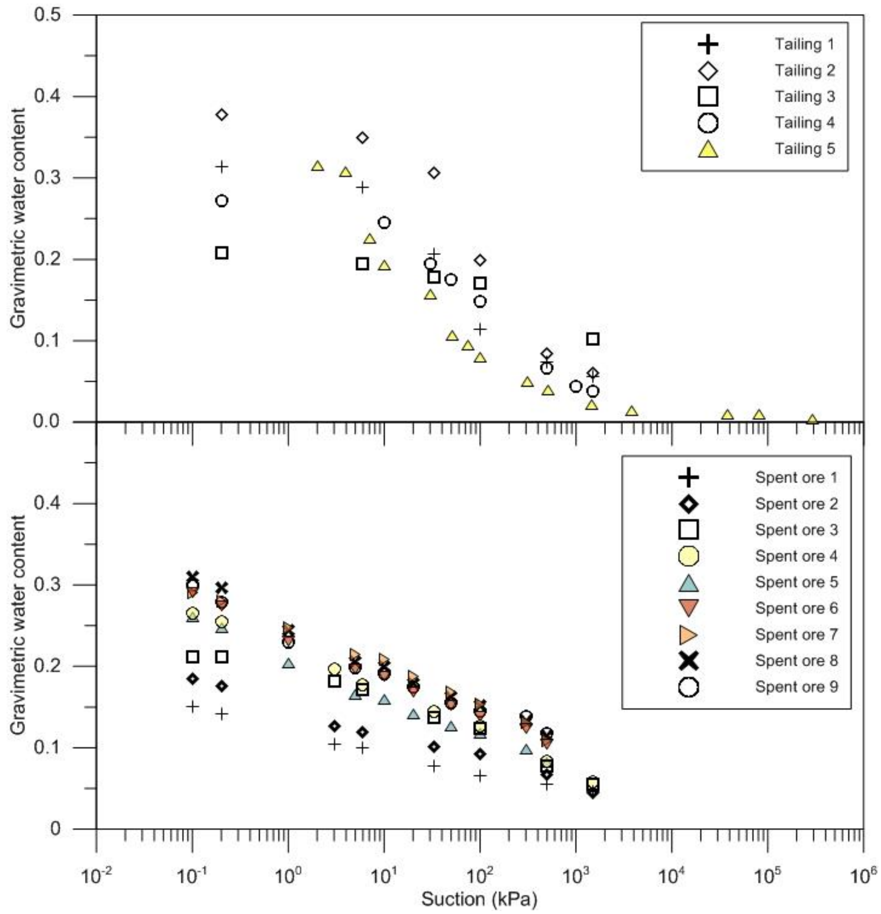

Figure 5. Experimental SWCC Tailing (upper) and Spent ore (lower).

In order to obtain a continuous representation of the SWCC, the experimental results were adjusted following the parametric models of van Genuchten [3] and Fredlund and Xing [4].

$$w(\psi) = w_r + (w_s - w_r)\left[\frac{1}{\left[1+(a_{vg}\cdot\psi)^{n_{vg}}\right]^{m_{vg}}}\right] \quad (1)$$

$$w(\psi) = w_s\left[1 - \frac{ln\left(1+\frac{\psi}{h_r}\right)}{ln\left(1+\frac{10^6}{h_r}\right)}\right]\left[\frac{1}{\left[ln\left[e+\left(\frac{\psi}{a_f}\right)^{n_f}\right]\right]^{m_f}}\right] \quad (2)$$

Where:

$w(\psi)$	Water content as a function of suction
ψ	Suction, capillarity or negative pore pressure
w_s	Saturation water content
w_r	Residual water content
a_f, n_f, m_f, h_r , a_{vg}, n_{vg}, m_{vg}	Fit parameter of the models

4 COMPARISON EXPERIMENTAL CURVES WITH SWCC ESTIMATION METHODS

Due to the relative difficulty present in the experimental determination of the SWCC, several methodologies have been developed to estimate it from some properties of the material to be studied. In the present study three different estimation methods have been considered, the first one corresponds to the one proposed by Fredlund & Wilson [5], which considers mainly particle size distribution properties and volume-mass relations, and making use of neural networks makes estimation. The second methodology used corresponds to the one proposed by Vereecken [6], which through a regression model determines the curve using as input parameters sand and clay percentages, the density and the carbon content of the material. Finally, Aubertin methodology [7] using the modified Kovacs method to estimate the porosity, density, void ratio, D10 and D60 of the material. For the application of the different methods of estimation and adjustment of curves, the Soilvision software [8] was used.

In order to quantify the differences between different estimates with respect to the experimental data, the Nash-Sutcliffe efficiency coefficient [9] was used, which measures the adjustment quality between two models and varies between $-\infty$ and 1; In this case, it has been considered that efficiencies above 0.9 are acceptable.

For this verification, six tailings from the literature corresponding to those described in references [7], [10] and [11] have been included in addition to the five tailings tested, and were named Relave 6 to Relave 11.

Table 2 shows a summary of the efficiencies of each estimation method with respect to the experimental data, it is possible to observe the great variability present in each case, however, the estimation through the Fredlund & Wilson method is the one that presents values better on average for the cases under study.

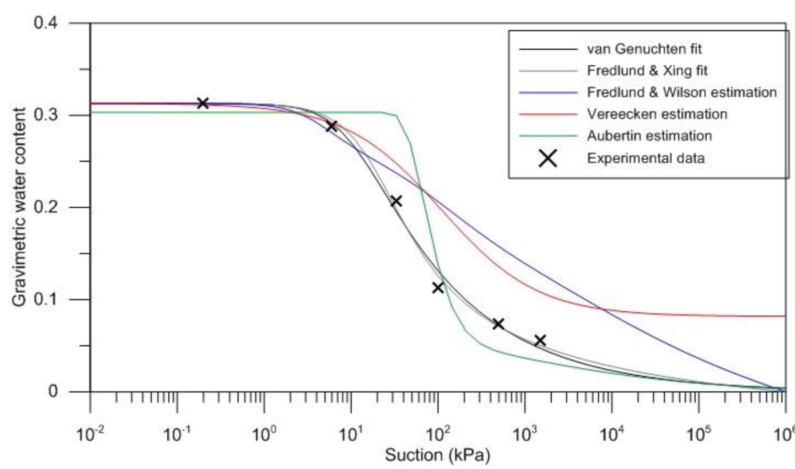

Figure 6. Comparison between fits, estimations and experimental data, tailing 1.

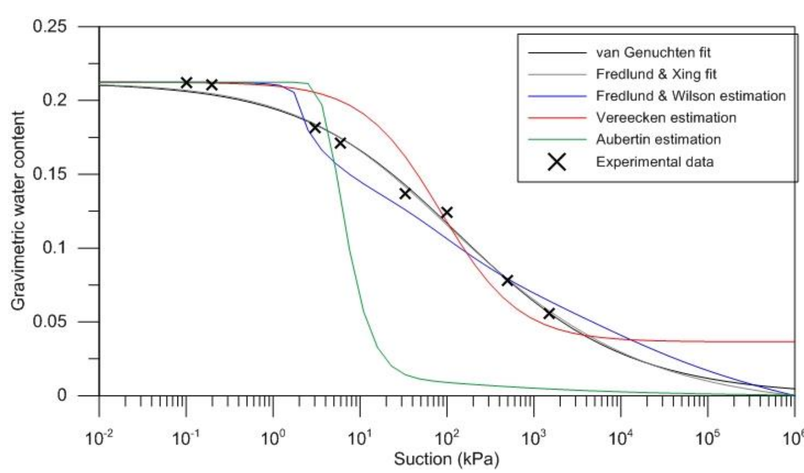

Figure 7. Comparison between fits, estimations and experimental data, spent ore 3.

Table 2. Estimation efficiency for each method.

Type	Name	Fredlund & Wilson	Vereecken	Aubertin
Tailing	Tailing 1	0.64	0.74	0.82
	Tailing 2	0.74	0.90	0.92
	Tailing 3	0.59	0.31	-5.08
	Tailing 4	0.82	0.97	0.40
	Tailing 5	0.93	0.94	0.51
	Tailing 6	0.93	0.95	0.71
	Tailing 7	0.76	0.78	-5.25
	Tailing 8	0.75	-0.45	-3.72
	Tailing 9	0.72	0.87	0.35
	Tailing 10	0.82	0.92	-0.77
	Tailing 11	0.78	0.92	0.06
Spent ore	Spent ore 1	0.95	-0.22	-2.30
	Spent ore 2	0.86	0.26	-1.94
	Spent ore 3	0.96	0.90	-0.58
	Spent ore 4	0.93	0.75	-0.11
	Spent ore 5	0.83	0.25	-3.04
	Spent ore 6	0.79	0.33	-4.82
	Spent ore 7	0.90	0.60	-6.17
	Spent ore 8	0.65	0.27	-4.59
	Spent ore 9	0.76	0.13	-5.62

5 ALTERNATIVE WORK FOCUS

Considering the values obtained in Table 2, the motivation to search for new alternatives that give similar results to the experimental results arises, without having to invest too much time or resources in its execution. Following the previous philosophy, it is proposed to perform a partial experimental determination of the retention curve, complemented by an adjustment method to fill the experimental gaps. In particular, it is proposed to perform the pressure plate test for only three points.

The points proposed for this methodology correspond to a low suction, whose associated humidity can be approximated to the saturation humidity of the soil; A high suction, equivalent to the point of wilting; And finally, an intermediate point, which in this case would be represented by the air entry value (AEV). The latter value was calculated for both the Fredlund & Xing and van Genuchten experimental fit, results are presented in Table 3.

Table 3. AEV for experimental fit VG y F&X

Type	Name	van Genuchten	Fredlund & Xing
		AEV (kPa)	AEV (kPa)
Tailing	Tailing 1	5.9	7.5
	Tailing 2	12.1	13.3
	Tailing 3	44.9	25.8
	Tailing 4	8.5	8.6
	Tailing 5	11.5	10.2
	Tailing 6	2.1	3.0
	Tailing 7	1.8	2.3
	Tailing 8	83.2	106.7

	Tailing 9	18.6	19.0
	Tailing 10	25.9	21.5
	Tailing 11	26.1	19.2
Spent ore	Spent ore 1	0.17	0.19
	Spent ore 2	0.27	0.18
	Spent ore 3	2.79	1.87
	Spent ore 4	0.42	0.33
	Spent ore 5	0.18	0.18
	Spent ore 6	0.20	0.15
	Spent ore 7	0.47	0.29
	Spent ore 8	0.13	0.16
	Spent ore 9	0.13	0.13

Average AEV for tailings corresponds to 22 kPa and for spent ore corresponds to 0.5 kPa. By adjusting these suction values to those typical of the laboratory, the values recommended in Table 4 are obtained.

Table 4. Selected suction values.

Point	Spent ore	Tailing
	Suction (kPa)	Suction (kPa)
1	0.1	0.1
2	1	30
3	1500	1500

Subsequently, the adjustment of van Genuchten and the adjustment of Fredlund & Xing with respect to the experimental curve were verified. For the tailings, both adjustments presented efficiency values close to 1. For spent ore only the Fredlund & Xing adjustment presents efficiency values close to 1, while van Genuchten delivers low values for four cases. The above is summarized in Table 5.

Table 5. Fit efficiency for each method.

Type	Name	van Genuchten	Fredlund & Xing
Tailing	Tailing 1	0.99	1.00
	Tailing 2	0.99	1.00
	Tailing 3	0.99	1.00
	Tailing 4	1.00	1.00
	Tailing 5	0.99	1.00
	Tailing 6	0.99	0.99
	Tailing 7	0.99	1.00
	Tailing 8	1.00	0.97
	Tailing 9	1.00	0.99
	Tailing 10	0.99	1.00
	Tailing 11	0.99	1.00
Spent ore	Spent ore 1	0.20	1.00
	Spent ore 2	0.34	0.99
	Spent ore 3	1.00	1.00
	Spent ore 4	0.99	0.99
	Spent ore 5	1.00	1.00
	Spent ore 6	0.27	1.00

	Spent ore 7	0.46	0.99
	Spent ore 8	0.93	1.00
	Spent ore 9	0.97	1.00

By way of example, Figure 8 shows fitting for tailings 1 and spent ore 3.

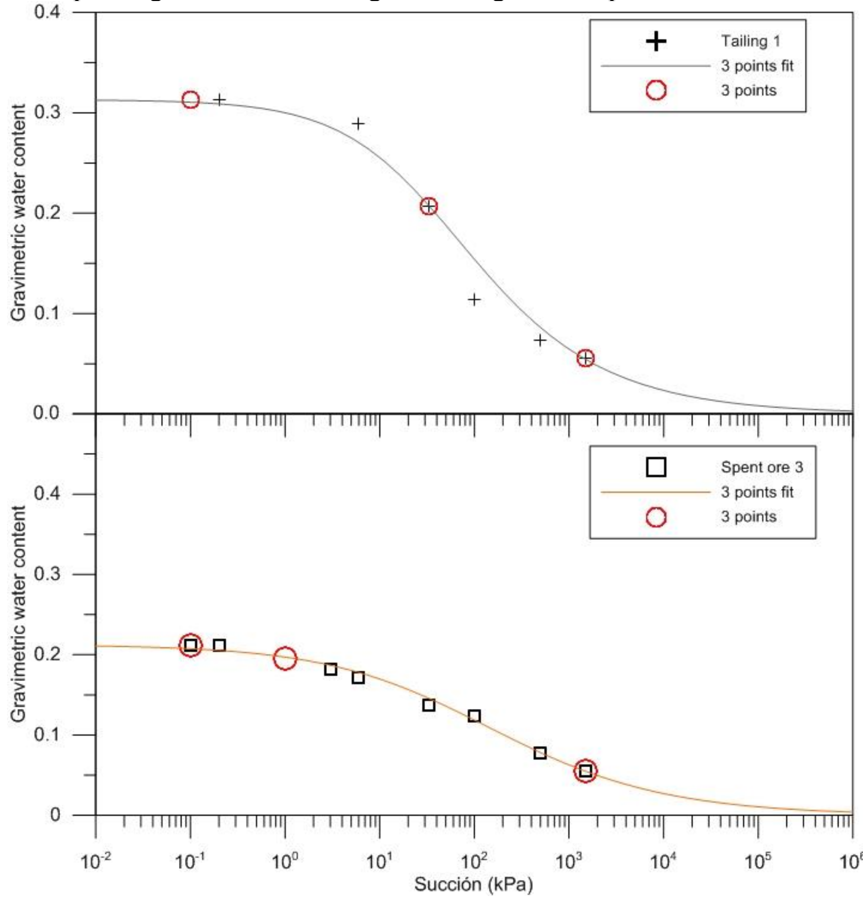

Figure 8. Example of fitting for tailings 1 (upper) and spent ore 3 (lower).

6 CONCLUSIONS

Moisture retention curves (SWCC) were experimentally determined for spent ore and tailings from different mining operations in Chile. These curves can be used as references for studies of unsaturated flow in deposits of tailings, spent ore dump and heap leach, with similar materials.

Experimental results obtained were compared with different estimation methods, finding that none represents the behavior satisfactorily for all the cases studied, according to the calculated efficiency. However, Fredlund & Wilson estimation proves, in general, to be superior to the others studied.

When the total determination of soil water characteristic curve is not possible, it is recommended to use the proposed three-point adjustment method, which includes the following suction values in addition to the saturation point of the sample: For tailings 30 KPa and 1500 kPa, while for spent ore 1 kPa and 1500 kPa. This alternative approach yields higher efficiency values than indirect estimates, representing a more reliable.

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