Partially saturated behavior of spent ore materials

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Abstract: Since the 1990s, heap-leaching operations have rapidly increased in South America, leading to a corresponding rise in mining waste, commonly known as spent leach ore stockpiles. The stability of these facilities is significantly influenced by the degree of saturation, fines content, and the phreatic level above the foundation soil. Understanding unsaturated soil mechanics is therefore fundamental. The soil water characteristic curve (SWCC) is crucial for understanding the unsaturated behavior of spent ore and its impact on stability. This paper reviews 39 spent ore samples tested for SWCC and saturated permeability, analyzing the results and evaluating how well the van Genuchten (1980) and Fredlund & Xing (1994) equations fit the data. Additionally, the effect of the ore sample's void ratio and fines content are discussed. This article presents a database of water retention curves for spent ore materials, which are scarcely available in the literature. Based on the data, it is concluded that the sample's void ratio is relevant at suctions prior to the air-entry value, and that no clear trend is observed regarding the influence of fines content within the studied range (less than 30%).

Introduction

In recent decades, copper production through solvent extraction and electrowinning (SX/EW) from leached oxide solutions has gained popularity in Chile and Peru due to its high recovery rates [1][2]. More recently, several mining companies have begun leaching sulphide ores by adding salt to the process, marking a significant industry shift. Traditionally, sulphide ores were processed via flotation to produce copper concentrate rather than pure copper.

The fundamental principle of copper heap leaching is straightforward: crushed rock is placed on a pad lined with a geomembrane and equipped with a drainage system to collect the solution. Heaps typically reach a height of about 10 metres. The pad is irrigated with a leaching solution, usually sulfuric acid, which dissolves the ore into a liquid that flows to the drainage system. Many mining companies continuously repeat this process, using a bucket-wheel reclaimer to remove leached material and a stacker to replace it. This method is known as on/off heap leach pad operation [2].

The spent leach ore (waste removed by the bucket-wheel excavator typically has a smaller particle size than the fresh rock initially placed on the heap, as it has been degraded by the leaching solution. After removal, it is usually transported via conveyor to a waterproofed dump and deposited by a stacker with a moisture content varying between 5% and 15%.

Spent leach ore dumps are typically designed with a waterproofed base and a drainage system, similar to a heap leach pad, and consist of four to eight lifts, reaching final heights of 80 to 150 metres. Slopes are generally based on the material's angle of repose, which for clayey gravel or poorly graded gravel ranges from 34° to 38° [3].

With declining ore grades and rising mining costs [2], many companies are optimizing processes and reconsidering the reprocessing of mine wastes, such as tailings and spent ore. Some mines now leach spent ore dumps to recover ore still trapped in gravel particles. These dumps, typically built without compaction, are usually in a very loose and partially saturated state. Understanding the hydro-mechanical behaviour of the material is essential to ensure the leaching solution does not compromise facility stability.

Analyzing these issues involves partially saturated soil mechanics, as spent ore dumps undergo continuous drying and wetting cycles [3, 4]. In this context, the soil water characteristic curve (SWCC) is essential for understanding moisture variation at different depths and predicting solution flow through such structures [5].

This research evaluates a dataset of SWCC and vertical saturated permeability results from various projects where SRK has been involved. SWCC fitting equations are applied to determine average fitting parameters and identify the best-fitting equation. Additionally, the effects of density (or void ratio) and fines content on the SWCC for this material are discussed.

Spent ore characterization

Basic properties

Copper spent ore is generally classified as a clayey gravel (GP-GC) with variable fines content (10–20%) and medium to low plasticity (PI < 15), typically falling under CL or CL-ML categories [3, 4]. However, material properties can vary significantly based on the geotechnical unit of origin and its reaction to acid during leaching. This process can make the gravel sandier, increase the fines content, and enhance moisture retention.

In the field, spent ore is typically deposited at a dry density of 14–18 kN/m^3 [3]. The moisture content ranges from 7–12% [3], corresponding to a saturation level of approximately 60–80%. When moisture exceeds 12%, depositing the material via conveyors becomes challenging.

Fig. 1(a) shows recently dumped spent ore, while Fig. 1(b) depicts a spent ore particle dumped one month earlier.

(a) (b)

Figure 1: (a) spent ore just dumped from the conveyor and (b) spent ore particle dried

This research studies 39 samples from seven different spent ore dumps. The particle size distribution is shown in Fig. 2, and Table 1 summarizes the main properties of the samples. Notably, all samples are from sulphide ore, except for Group 3, which corresponds to oxide ore.

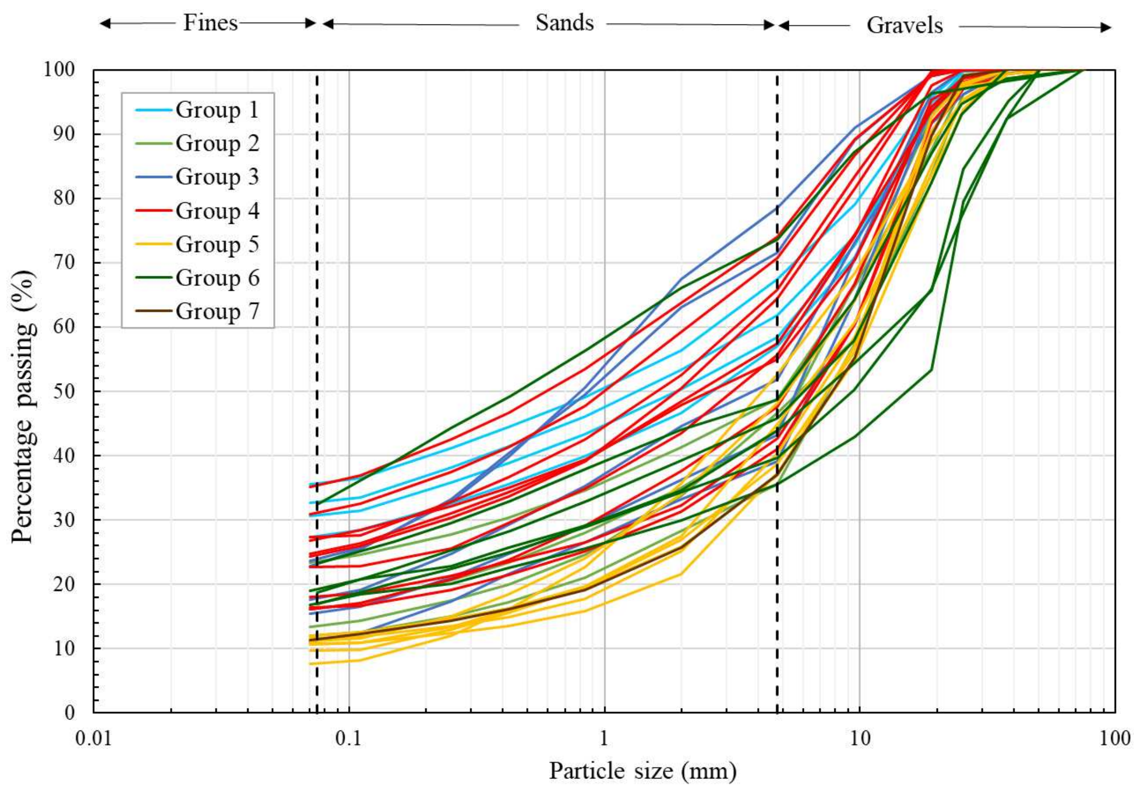

Figure 2: Particle size distribution of groups under analysis.

Table 1: Average properties of the spent ore materials under study

Group	*Gravel (%)*	*Sand (%)*	*FC (%)*	*PI (%)*	*USCS classification*	*In-situ dry density (kN/m³)*
1	39	30	32	30	GC	15,5 – 16,5
2	56	28	16	9	GC	16,0
3	43	39	18	13	GC & SC	16,0 – 17,5
4	56	28	16	9	GP-GC	15,0 – 16,8
5	57	32	11	11	GP-GC	15,0 – 1,75
6	50	27	21	13	GC	18,9 – 19,8
7	63	26	11	11	GP-GC	14,5 – 18,0

Saturated hydraulic conductivity

All groups were tested for saturated vertical hydraulic conductivity using both flexible and stiff tubing tests to determine permeability at different densities or void indices. Fig. 3 shows the results for 24 samples with varying densities and fines content (FC).

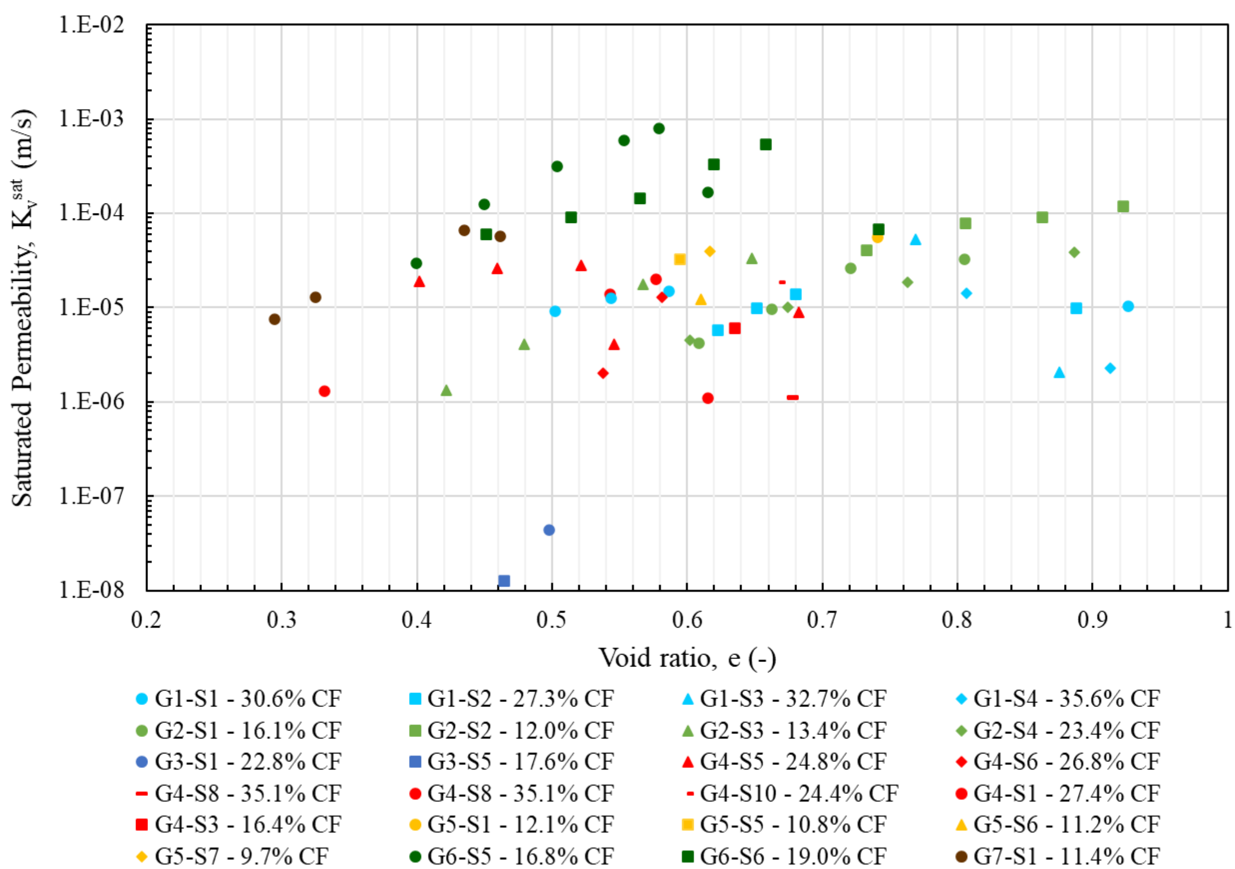

Figure 3: Saturated vertical hydraulic conductivity of samples under analysis

Based on the results, all groups have a saturated vertical permeability (k_v^{sat}) ranging from $1{\cdot}10^{-3}$ to $1{\cdot}10^{-6}$ m/s, with data concentrated between $1{\cdot}10^{-4}$ and $1{\cdot}10^{-5}$ m/s, except for Group 3, which has a k_v^{sat} lower than $1{\cdot}10^{-7}$ m/s. Additionally, there is a slight trend suggesting that a lower void index correlates with lower hydraulic conductivity.

Samples with fines content below 20%, had minimal impact on permeability but when the fines content exceeds 20%, vertical permeability is reduced, regardless of the void ratio.

SWCC results

Fig. 4 shows the drying path of the SWCC for the 39 samples analyzed in this study. All samples were tested using pressure plate devices with the axis translation technique [6], except for Group 6, where a large Tempe Cell with a suction range of 0–65 kPa was combined with a chilled mirror psychrometer (relative humidity control method) for suctions over 1500 kPa.

The pressure plate device was used to determine gravimetric water content at matrix suctions of 10, 30, 50, 100, 500, 1000, and 1500 kPa. Saturation moisture (moisture saturation?) was estimated using the specific gravity and sample preparation void ratio, assuming S_r = 100% for each sample, and was set to 0.1 kPa for data presentation (see Fig. 4).

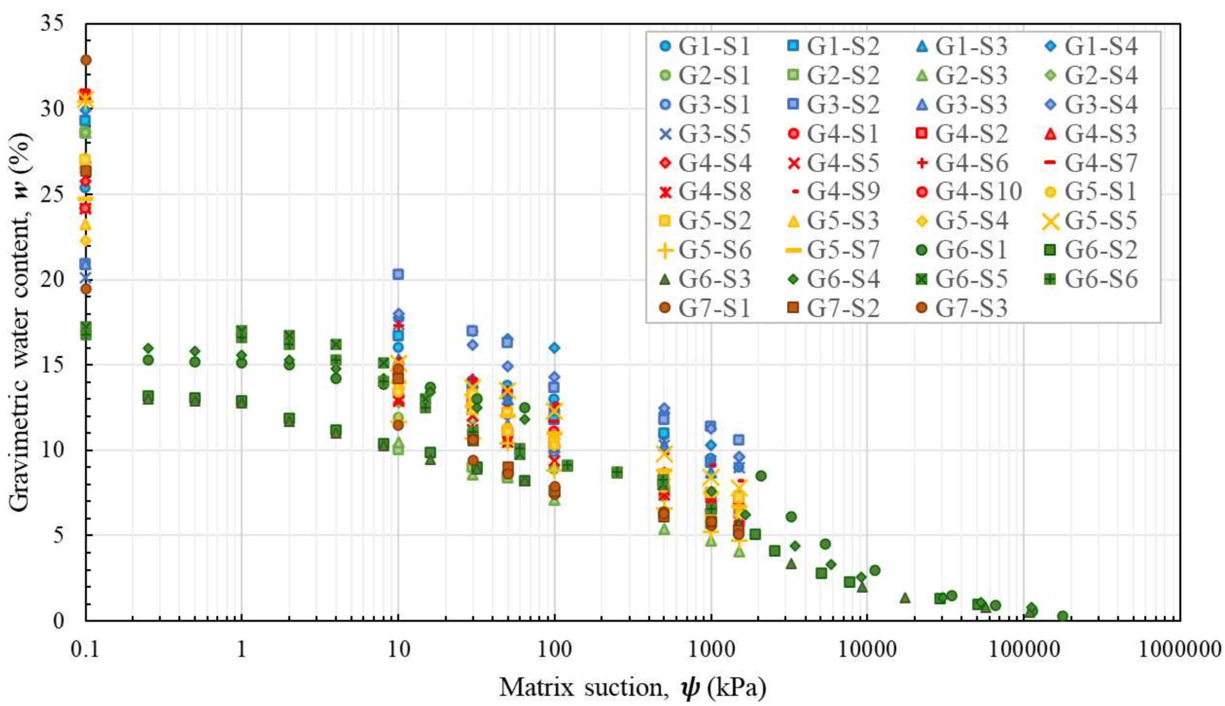

Figure 4: SWCC for the samples under analysis

From Figure 4 There is a lack of data for suctions below 10kPa, this is due to the limitations of the pressure plate device. Therefore, the results suggest that the air-entry value (ψ_{AEV}) cannot be calculated in a straightforward manner. For high saturation values, the air is not continuous in the soil sample and is difficult to measure matrix suction since occluded bubbles can be found in the pore water. However, results from Group 6, which includes six measurements below 10 kPa, show that ψ_{AEV} lies between 1 and 5 kPa. The residual zone is reached near 5000 kPa, based on Group 6 data.

Empirical equations fitting

Many empirical equations have been proposed to fit laboratory data for SWCCs. In this research, three-parameter SWCC equations were used to fit the laboratory data. Specifically, the van Genuchten (1980) [7] and Fredlund & Xing (1994) [8] equations, shown as Eq. 1 and 2, respectively, provided the best fit.

$$w(\psi) = w_r + (w_{sat} - w_r)\left(\frac{1}{\left(1 + \left(a_{vg}\psi\right)^{n_{vg}}\right)^{m_{vg}}}\right) \tag{1}$$

$$w(\psi) = C(\psi)\frac{w_{sat}}{\left(e + \left(\psi/a_f\right)^{n_f}\right)^{m_f}} \tag{2}$$

Where C(ψ) is a correction factor that transforms the Fredlund and Xing (1994) equation into a 4-parameter (a_f, n_f, m_f, h_r) continuous equation valid up to $1{\cdot}10^6$ kPa [9], as shown in Eq. 3:

$$C(\psi) = 1 - \frac{ln\left(1 + \frac{\psi}{h_r}\right)}{ln\left(1 + \frac{10^6}{h_r}\right)} \tag{3}$$

Equation fitting was performed using mean square error regression analysis, as shown in Eq. 4:

$$MSE = \frac{1}{n} \cdot \sum_{i=1}^{n}(w_i - w_i^*)^2 \tag{4}$$

where *n* are the measured points per sample, w_i is the gravimetric water content measured at a given suction and, w^*_i is the gravimetric water content estimated by each fitting equation.

Zhai & Rahardjo (2012) [10] defined the Fredlund & Xing (1994) equation as "Method A" when the correction factor C(ψ) is used, and "Method B" when C(ψ) = 1.0. Table 2 presents the average properties for each parameter of both methodologies, while Fig. 5 shows the MSE from the data fitting of each equation.

From Fig. 5, the Van Genuchten (1980) and Method B equations produce similar MSE errors, while Method A tends to exhibit a higher MSE. The highest MSE values are found for Group 6, where data fitting is complex due to the intersection between the Tempe cell and hygrometer data (matrix suctions between 100 and 1000 kPa). However, for Group 6, Method A provides the best estimations.

Table 2: Average fitting values obtained for each group

Group	van Genuchten			*Fredlund & Xing (A)*				*Fredlund & Xing (B)*		
	a_{vg}	n_{vg}	m_{vg}	a_f	n_f	m_f	h_r	a_f	n_f	m_f
1	6.0	9.8	0.0	0.1	4.7	0.0	800.0	0.2	4.2	0.0
2	10.3	8.7	0.0	0.1	10.0	0.0	750000.0	0.1	8.9	0.0
3	2.5	6.5	0.0	1.0	2.7	0.0	1.2	2.6	4.9	0.2
4	5.1	4.8	0.1	0.1	6.4	0.0	4353.0	0.5	5.8	0.1
5	5.4	5.0	0.0	0.1	7.2	0.0	3557.6	1.6	3.9	0.2
6	0.2	1.4	0.3	200.4	6.2	0.1	29.6	167.4	9.9	0.0
7	3.6	3.1	0.1	0.1	6.6	0.0	0.4	0.5	1.8	0.2

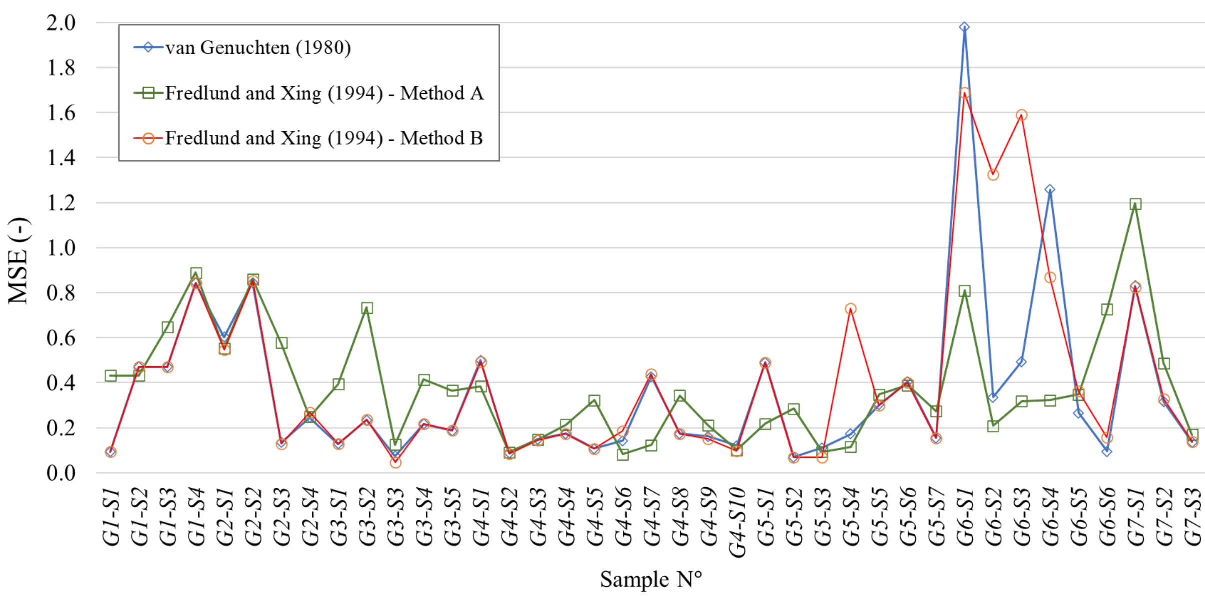

Figure 5: MSE obtained for van Genuchten (1980) and Fredlund & Xing (1994) fitting equations

Particle size distribution influence

Previous research has proven that the SWCC depends on soil type. Finer soils tend to have higher ψ_{AEV} and a lower slope of desaturation [5, 11]. While initial water content depends on factors such as initial void ratio, fine soils also store more water at low suctions. Fig. 6 shows the results for Group 4 and data fitting based on the van Genuchten (1980) procedure. All samples were prepared to the same dry density of $\gamma_d = 16\ kN/m^3$or void ratio of e=0.69 (w_{sat}=24.3%).

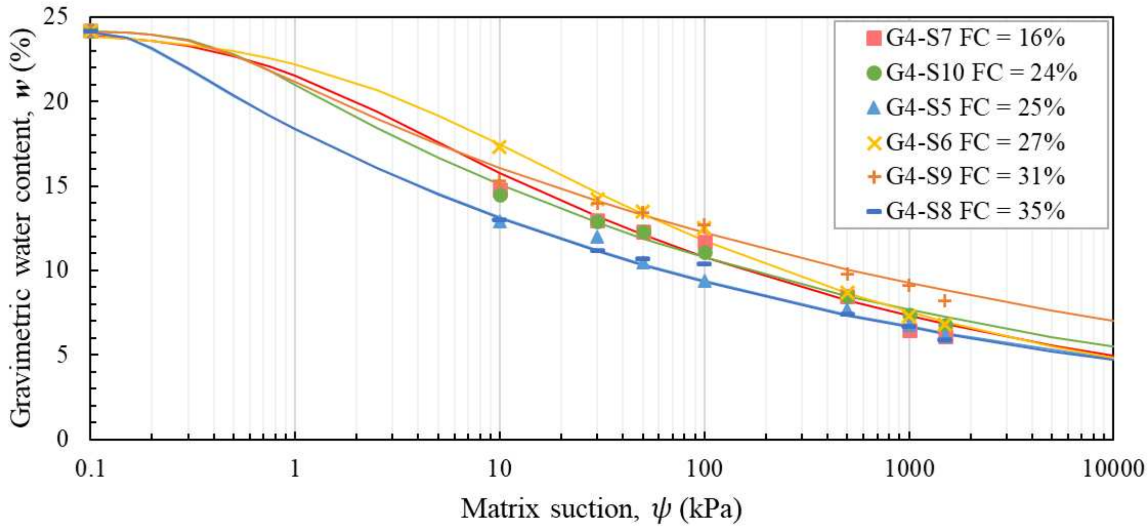

Figure 6: van Genuchten (1980) SWCC fit obtained for group 4 samples, considering same unit weight and different fines content

From Fig. 6, no trend is observed regarding fines content, ψ_{AEV}, residual conditions, or the desaturation slope. For example, the sample with the lowest fines content (G4-S7) follows the average trend of the different curves, and the sample with higher fines content exhibit a behavior similar to a coarser material (steeper desaturation slope and lower ψ_{AEV}). These results indicate that, for coarse materials such as spent ore samples, fines content does not play a crucial role in the SWCC determination. However, a larger dataset should be assessed in order to establish clear trends.

Void ratio influence

The influence of the void ratio on the SWCC has been studied exhaustively [11]. There are several studies suggest that there is an increase in soil suction and ψ_{AEV} with a lower void ratio. Furthermore, it has also been observed that the void ratio effect tends to be more predominant for fine-grained soils than for coarse-grained soils [11, 12]. However, there are also studies that demonstrate that the soil suction is independent of unit weight of soil [11,13].

Fig. 7 shows the results for three identical samples (FC=11%) from Group 7 prepared at different void ratios (e=0.91, 0.73 and 0.54). It is evident that an increase in the void ratio will increase the water content required to achieve 100% saturation which causes the most notable difference between the curves. However, for matrix suctions higher than 10 kPa the gap between the obtained results for each suction tend to be insignificant (less than 1% of gravimetric water content.

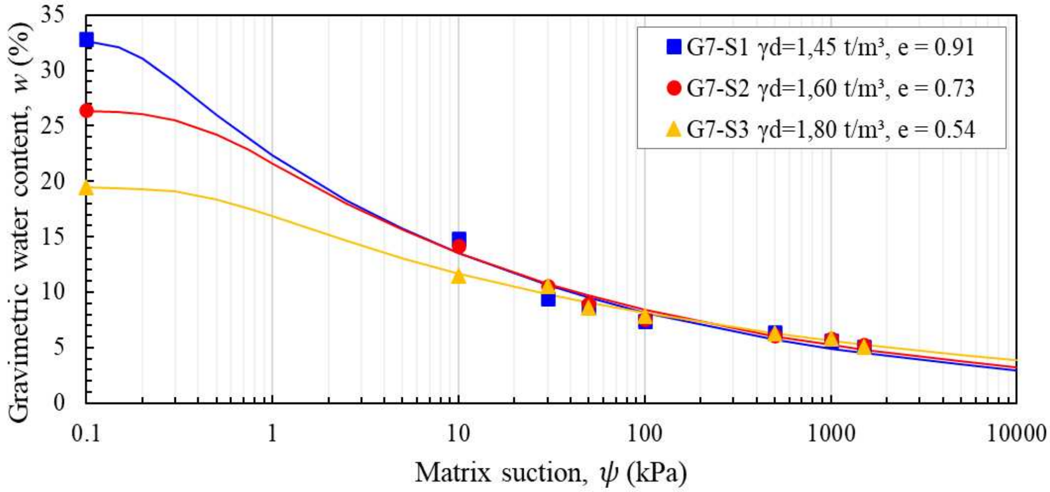

Figure 7: SWCC obtained for group 7, considering same different void ratios

Conclusions

Nearly 40 samples of spent ore material were analyzed for both SWCC and saturated permeability in commercial laboratories in Chile. Most samples were classified as clayey gravel soil (GP or GC) with fines content ranging from 10% to 30%, and fines of medium to low plasticity (PI < 15%), except for one group with PI = 30%.

All groups exhibited saturated vertical permeability ranging from $1 \cdot 10^{-3}$ to $1 \cdot 10^{-6}$ m/s, with most data concentrated between $1 \cdot 10^{-4}$ to $1 \cdot 10^{-5}$ m/s. Additionally, there is a slight trend indicating that a lower void index correlates with lower hydraulic conductivity.

For the SWCC results, assessing the air-entry value using the pressure plate device proved to be challenging, as the equipment relies on a continuous air phase in the soil, something difficult to achieve at low suctions and high saturation values. Consequently, the gravimetric water content at 10 kPa already falls within the desaturation zone of the material. It is recommended to use tensiometers devices (axis translation technique) or the control of relative humidity method by using a psychrometer.

Results from Group 6, obtained with Tempe cells, which included six measurements below 10 kPa, show that the air-entry value lies between 1 and 5 kPa, confirming the need for measurements in this suction range. The residual zone is reached near 5000 kPa.

For each group, a trend emerges: for suctions above 50 kPa, results tend to be similar regardless of density or fines content within the studied range. However, density or void ratio plays a more influential role at lower suctions, near the air-entry value. No clear trend is observed in the data regarding fines content, where six samples with fines content between 16 and 35% were analyzed in terms of their SWCC results.

Regarding SWCC fitting, both Fredlund and Xing (1994) with C = 1, and the van Genuchten (1980) model provide good results for most of the soils tested with the pressure plate device.

However, for Group 6, tested with tempe cells and complemented by hygrometer tests, the best fit is achieved with the Fredlund and Xing (1994) 4-parameter equation (i.e., C ≠ 1).

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