Unsaturated shear strength parameters for a compacted iron ore tailings

Michelli Hora de Jesus[1], *Rodrigo Serafim*[2], *João Paulo Silva*[3], *Fernando A. M. Marinho*[4]

[1] Master's student at IGC-USP, São Paulo, Brazil
[2] Engineer at the Technological Research Institute of the State of São Paulo (IPT) and Master's student at IGC-USP, Brazil.
[3] Engineer at Vale S.A., Minas Gerais, Brazil.
[4] Associate Professor at USP, São Paulo, Brazil

Abstract. The use of iron mining tailings in compacted landfills is expected to expand more and more to replace the placement of tailings in dams. With this, the unsaturated condition of these materials becomes of great importance for the safety of the structures executed with them. In addition to tests in the saturated condition, and with the objective of simplifying the determination of strength parameters in the unsaturated condition, direct shear tests with constant water content were performed. Data of physical and chemical characterization of the tailings, and the water retention curve at the compacted state and continuously disturbed condition are also presented. The latter aims to evaluate the effect of the shear process on the final suction of the material. The results suggest that there are no significant variations in suctions during the failure process and that, in this case, the initial suction can be assumed to be the same as the one at failure. The shear strength parameters indicate a high friction angle, which does not vary with suction. With the data obtained, it was possible to apply the model of Vilar (2006) to obtain the shear envelope with suction. The results presented aim not only to expand the database of iron ore tailings parameters, but also to present a procedure for the application of tests with constant water content.

1. Introduction

Brazilian iron ore reserves represent 19.8% of world reserves, with an average content of 46.2% of iron, being the second largest producer in the world ranking. The main states with iron ore reserves are Minas Gerais with 74.4% of reserves and an average content of 41.1%, Pará with 19.5% of reserves and an average content of 65.6% and Mato Grosso do South with 2.2% of reserves and an average content of 63.7%. [2].

According to Carlos [3] and Pereira [11], The Quadrilátero Ferrífero (QF) comprises an area of about 7000 km2 and hosts one of the largest concentrations of lateritic iron-ore deposits in the world. The QF is located in central Minas Gerais state, southeastern region of Brazil [6]. Mining companies explore the mineral in the region resulting in significant volumes of waste, including tailings and waste rock (Material without economic value that generally covers the deposit). The processing of iron ore and mining generate significant amounts of tailings and waste rock, with an average ratio of 2 to 1 between the final product and the generation of tailings (e.g. [7]).

Waste rock dumps are deposited in thalwegs and slopes close to the mining. Tailings are residues from the mineral beneficiation process, deposited in the form of pulp or mud in reservoirs known as tailings dams. Tailings are also deposited in the form of landfills when these tailings are subjected to a water removal process.
The extraction of iron ore comprises several activities in which it will determine the characteristics of the residues in the process. The final characteristics vary according to the technology used in the industrial process and the quality of the raw material. Therefore, the tailings have varied physico-chemical, geotechnical and mineralogical characteristics [5].
The essential processes in mining to obtain iron ore are represented in Figure 1.

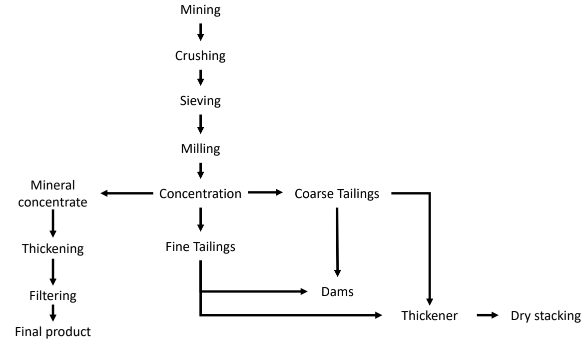

Fig. 1. Flowchart of iron mining processes. (Mod. from [1]).

Bearing in mind the beneficiation processes and the natural variability of the mining fronts, iron ore tailings have heterogeneous characteristics from the granulometric point of view and in some mineralogical cases, and there may be fine or coarse tailings, plastic or non-plastic.

In the case of filtered dry stack tailings facilities or tailings dump, resistance characteristics are extremely important to guarantee stability. In many cases the piles is designed to work in the unsaturated condition and transient flow studies contribute to the assessment of this state of saturation throughout the life of the tailings structure.

The determination of the strength parameters of unsaturated material is still a limitation of the actual application of the concepts of mechanics of unsaturated soils. Commercial laboratories have technical and personnel difficulties to execute the tests. However, it is considered that these difficulties can be reduced when performing tests with constant water content.

Tests in the unsaturated condition, using mining tailings, is not common in the literature. This type of material has characteristics that require further investigation. This paper presents preliminary results of these studies.

2. Constant water content shear test

Shear strength tests on unsaturated soils are not commonly performed in engineering practice. One of the reasons is the difficulty in controlling the suction during the test and also due to the lack of training of the professionals who perform the tests. Among the tests that can provide resistance parameters for use in engineering practice, the test performed keeping the moisture content constant seems to be promising for use in practice. Figure 2 illustrates the failure surface of any material. Point T represents the condition after consolidation under a given vertical load. Paths A, B and C are possible paths that suction can follow during the shearing process, representing reduction, increase and constant suction, respectively. The cohesion intercept (which includes suction) based on the failure envelope is obtained by extending the envelope to the plane of zero normal stress.

Ideally, the tests should be carried out with direct suction measurement (e.g. [15]; [10], among others) but this technique is not widely used in most research laboratories and practically in no commercial laboratory. Thus, the search for understanding the development of pore pressure during shear in unsaturated soils is essential to expand the use of concepts of mechanics of unsaturated soils.

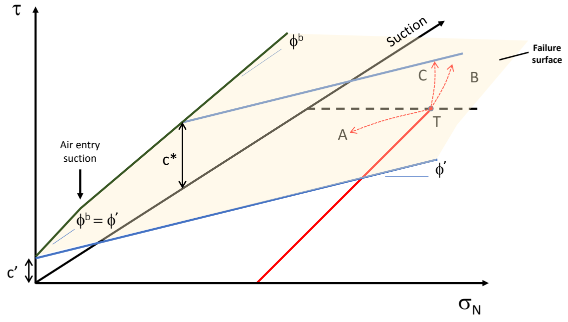

Fig 2. Possible suction path during a constant water content test.

Croney & Coleman [3] were possibly the first to present data on suction at failure, represented using the water retention curve. Figure 3 schematically shows three retention curves for the same material. One of them represents the drying SWRC of a sample prepared in the slurry condition, another representing the natural condition, which can be compacted, and the curve that represents the relationship between water content and suction at failure, called continuously disturbed.

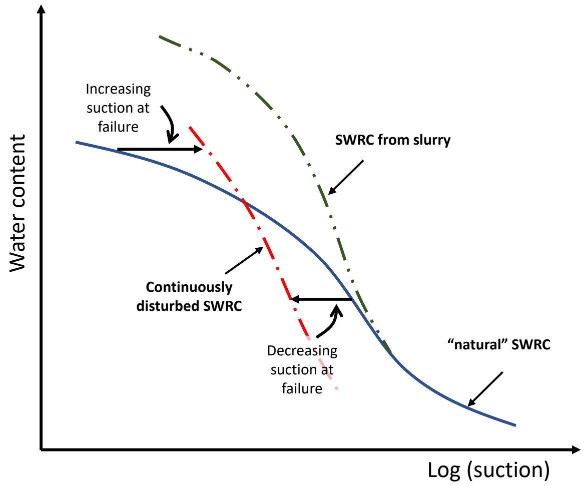

Fig 3. Schematic representation of the SWRC under three conditions.

The continuously disturbed SWRC concept needs further studies, but it is conceptually fundamental for shear strength tests performed under constant moisture content. Aspects associated with suction variation in relation to volume variations during the failure process are fundamental. Rahardjo et al [12] observed that the variation in suction during shearing is not directly related to the volume change of the material during the test, in the way we usually measure it. Rahardjo et al [12] call attention to the importance of air entry suction as a reference for increasing or reducing suction, and present some considerations about the expected behavior for the material tested by them. The soil behavior before and after air entry suction should be further investigated.

Rahardjo et al. [12] used the axis translation technique to carry out triaxial tests with constant water content, in residual soil from the Jurong sedimentary formation. For suctions above the air entry suction (100 kPa) the suction at failure was always lower than the initial one. The suction reduction was greater for higher confining stresses. Thu et al [15] tested compacted kaolin and observed that suction suffered a reduction in failure compared to the initial value. Suction measurements were made with a high-capacity tensiometer (HCT) installed on the side of the triaxial specimens. Suction variations ranged from 20% to 30%, with a greater reduction for higher suctions. It should be noted that after the air entry suction, the role of suction becomes smaller, that is, it has a lower fib value. Oliveira et al. [10] also carried out measurements with HCT and the results indicate that the suction variations for the compacted residual soil tested, the suction variations were between 0 and 25% (decreasing) of the initial value. The largest variations were for higher initial suctions. Uyeturk & Huvaj [16] present results of direct shear tests performed with a residual soil of volcanic origin, but the suctions were not measured during the tests. The interpretation was based on the degree of saturation and on the total volume variation of the specimens, which makes it difficult to assess the effect associated with the suction behavior in failure. Rahardjo et al [12] conclude that suction in the CW tests is not related to the volume change of specimens during shearing. Vo et al. [18] uses the principle of effective stresses, applied to ore in the unsaturated condition, to infer the mechanical behavior of the material, thus simplifying the application of concepts associated with unsaturated soils.

3. Tested Material

Table 1 presents information on the geotechnical characterization of the tested material. The material cannot be classified by the Unified System, as it has a quantity of fines greater than 50%, but does not have any plasticity. The compaction curve presents a flat format with a variation between the dry branch (8%) and the wet branch (16.4%) in relation to the optimum of only 0.67 kN/m3 and 1.1 kN/m3, respectively.

Table 1. Material characteristics

Parameter	Value
% <2 µm	5%
Silt	35%
Fine sand	56%
Medium sand	4%
G_s	3.1
D_{10}	0,0046 mm
D_{30}	0,035 mm
D_{60}	0,068 mm
Uniformity Coefficient (C_u)	14,78
Coefficient of Curvature (C_c)	3,92
$\gamma_{d\text{-max}}$	2.02 kN/m^3
w_{opt}	12%

In addition to the trandicional geotechnical characterization, analysis was performed by X-ray diffractometry using the powder method for chemical and mineralogy characterization, using the Bruker model D8 Advance Da Vinci equipment with Lynxeye detector and Twin-Twin optics. In addition, physical analyzes of the grains of the milling brand, size, shape of the grains and chemical analyzes were carried out, by means of Scanning Electron Microscopy (SEM) using the equipment branded LEO model 440i.

The mineral phases present in the tailings sample obtained by X-ray diffraction indicated the following composition: quartz and hematite, with goethite, muscovite and kaolinite and others minerals that occur in smaller proportions. The analyzes carried out in scanning electron microscopy (SEM) made it possible to evaluate morphologically and chemically the particles present in the tailings. Figure 3a shows the shape of the grains of the larger particles, measuring approximately 100 µm, ranging from sub-rounded to angular, consisting predominantly of quartz grains, with peaks in the Si and O elements. In addition, adhering to these particles it is observed fine to powdery material as can be seen in Figures 3b and 3c. The smaller particles vary from sub-rounded to angular with quartz compositions, and eventually hematite occurs in tabular forms. Particles classified as very fine are slightly rounded. A typical Electron Scatter Spectroscopy (EDS) containing quartz and hematite is presented in Figure 4, with peaks in the elements of Fe, O, Si and Al, and occurrence of Ti, Cu and K in smaller proportions.

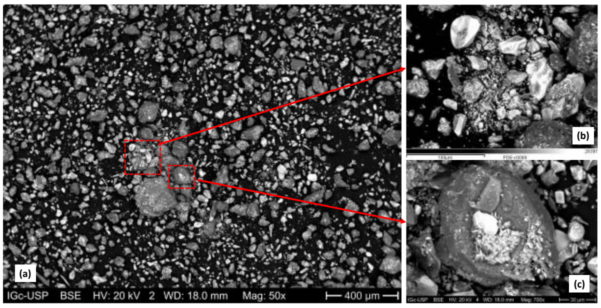

Fig. 3 Photomicrographs on a 400 µm scale with grains ranging from sub-rounded to angular, consisting predominantly of quartz grains; (b) and (c) Presence of fine to powdery material adhered to the quartz grains.

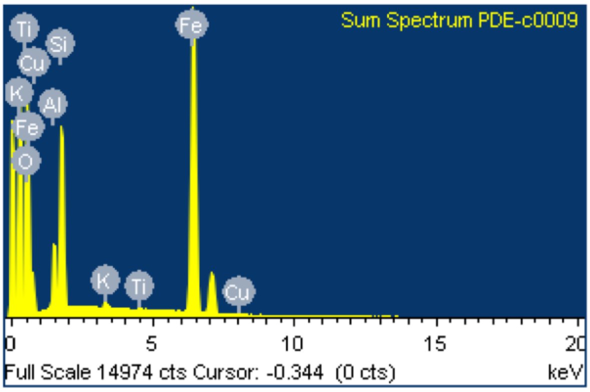

Fig 4. Electron Scatter Spectroscopy (EDS) of iron ore tailings.

4. Testing Method

The data presented in this paper refer to a clayey silt iron ore tailing. To determine the strength parameters of the tailings, direct shear tests were performed on compacted samples. The samples were compacted using the energy of the Standard Proctor, but which reached a degree of compression ranging from 101% to 103%. A total of three samples were compacted at this condition.

The direct shear tests were performed in the saturated and unsaturated conditions, in both, the shear step started after the complete stabilization of the consolidation. The shear speed adopted was 0.183 mm/min. After the first shear process, it was manually induced in the specimen, ten back and forth, in an attempt to obtain the post peak strength. Before the second shear, it was waited one hour for eventual pore pressures to dissipate.

5. SWRC

The water retention curve for the tested material was obtained using the WP4C dewpoint potentiameter, under two conditions: as compacted and under continuous disturbance. This last condition would represent the condition in failure. SWRC was also obtained using the traditional suction plate and pressure plate methods. Figure 5 presents the data obtained.

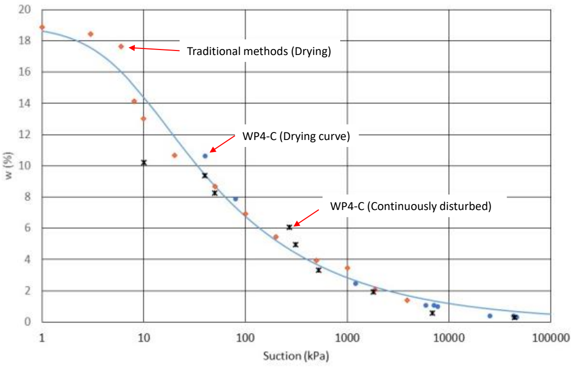

Fig 5. Soil water retention curve for different methods and conditions.

It is observed that the data obtained with the WP4C compare well with the data obtained by the traditional methods. Continuously disturbed condition data were obtained by manually destroying the specimen's structure at each measurement. This procedure requires further investigations, but the results suggest that for the tested material the suction at failure is similar to the initial one.

6. Direct shear test

In the saturated condition, three samples were subjected to direct shear with normal stress equivalent to 50, 100 and 200kPa. The specimens were simultaneously subjected to saturation and consolidation under the chosen normal stress. At the end of the test, the water content of the specimen was determined and then the void index, degree of saturation and dry density of the specimens were calculated.

Two specimens were sheared in the unsaturated condition. In these two tests, a vertical load of 19 kPa was used. One of the specimens was subjected to direct shear in the condition as compacted, that is, right after compaction, with a moisture content of 11.6%. The second specimen was allowed to air dry for about 4 days, and then subjected to direct shear. The objective of the test with an air-dried sample was to use the result to apply Vilar's model [17].

Table 2 presents the initial data of the specimens, in addition to the final water content and the normal stress used in each tests. The samples tested in the unsaturated condition were submitted to a minimum normal stress to obtain information as close as possible to the null normal stress condition. One of the specimens was tested in the air-dried condition, in order to apply the Vilar´s model [17].

Table 2. Data from specimens tested

Condition	Sample	Specimen	w_i (%)	γ_{di} (g/cm^3)	e_i	S_i (%)	w_f (%)	σ_N (kPa)
Soaked	SP01	1	11.95	2.092	0.482	76.9	14.83	50
	SP02	2	12.2	2.059	0.506	74.8	14.49	100
	SP02	3	12.2	2.059	0.506	74.8	12.86	200
Unsaturated	SP03	4	12.5	2.069	0.498	77.8	11.64	19
	SP03	5	12.5	2.069	0.498	77.8	0.8	19

The results obtained in the direct shear tests allowed obtaining the shear strength envelope in the flooded condition (zero suction) and in two other conditions. In one of them the material was compacted and allowed to dry in the air, and in the other the drying was partial, taking the specimen to a suction of 41 kPa according to SWRC.

Figure 6 shows the envelopes in the soaked condition and the one obtained after 10 manual runs of the shear box. This last procedure aimed to obtain the post peak envelope. The envelopes for the two unsaturated conditions of the material are also presented. It was assumed that the effective friction angle does not change with desaturation.

The value of the effective friction angle of the studied tailing (48º) is quite high, but it is in agreement with data obtained by other authors for similar material (e.g. [14]). Even for the post peak condition, the friction angle is high and equal to 36º.

The estimation of the failure envelope in terms of suction was made using the model presented by Vilar [17]. The model uses equation 1 to obtain the cohesion intercept (c*) associated with suction (*s*).

$$c^* = c' + \frac{s}{a+b*s} \qquad [1]$$

Where a and b are curve fitting parameters. The values of a and b can be obtained using the following expressions.

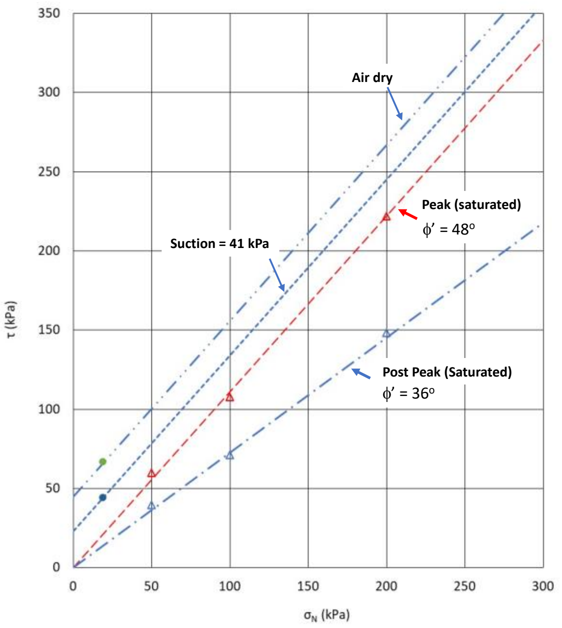

Fig 6. Failure envelopes obtained.

$$\frac{1}{a} = tan\emptyset' \qquad [2]$$

And

$$b = \frac{1}{(c_{ult} - c')} \qquad [3]$$

Where, c_{ult} is obtained with the specimen tested in the air-dried condition.

Figure 7a presents the result of applying the previously mentioned model to the initial part of the failure envelope, where the result of the test with a suction of 41 kPa is also presented. Note the good fit obtained. Figure 7b presents the complete adjustment just for reference to the cohesion position obtained in the air-dry condition, where a suction of 30 MPa was estimated.

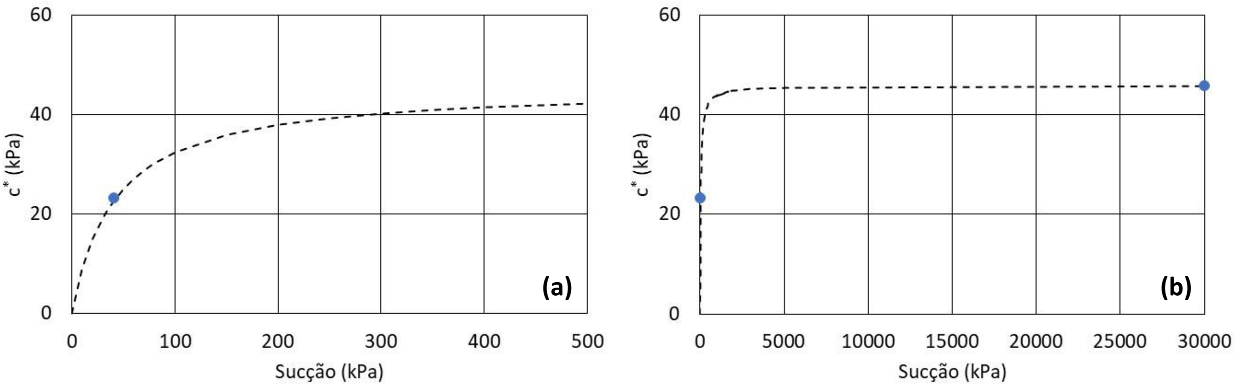

Fig 7. Shear strength envelope obtained (a) for low suction values and added experimental data (b) complete envelope.

7. Conclusions

The preliminary data of the project that involves the study of the behavior of some iron mining tailings from Minas Gerais (Brazil), allowed to evaluate some important aspects of the shear strength of the tailings and also to evaluate the application of the model of Vilar [17] to the data obtained. In addition, the SWRC of the material in the continuously disturbed condition was obtained on a preliminary basis. The main conclusions obtained can be summarized as follows:

The friction angle of the waste was high, according to data found in the literature for similar material. The shape of the grains and the structure obtained must be responsible for these high values.

Villar's model [17] proved to be an important tool to estimate the behavior of the material in the unsaturated condition. Although only one intermediate point was evaluated, this data proved to be very consistent with the model.

For suctions lower than the desaturation point, that is, air entering the sample, the friction angle is equivalent to the effective friction angle determined in shear in the saturated condition ϕ' = 48° . However, with the entry of air, there is a decrease in the friction angle in ϕ^b, as recommended by the model by Villar [17].

Although the tested material does not show plasticity, no loss of shear strength was observed in the unsaturated condition, even for the air-dried condition.

References

1. Albuquerque Filho, L. H., Ribeiro, L. F. M., Pereira, E. L., & Gomes, R. C. (2004). Evaluation of the In Situ Density of an Iron Mining Tailings Dam with the Penetrologger. In Brazilian Congress of Science and Technology in Waste and Sustainable Development.
2. ANM. National Mining Agency. Mineral Summary (2018). Available at: <https://www.gov.br/anm/pt-br/centrais-de-conteudo/publicacoes/serie-estatisticas-e-economia-mineral/sumario-mineral/pasta-sumario-

brasileiro-mineral-2018/ferro_sm_2018>. Accessed in October, 10th, 2022.

3. Carlos, D. U., Uieda, L., & Barbosa, V. C. (2014). Imaging iron ore from the Quadrilátero Ferrífero (Brazil) using geophysical inversion and drill hole data. Ore Geology Reviews, 61, 268-285.
4. Croney D & Coleman JD (1954) Soil structure in relation to soil suction (pF). Journal of Soil Science 5:75–84.
5. Dorr, J.V.N. (1965). Nature and origin of the high-grade hematite ores of Minas Gerais, Brazil. Econ. Geol.
6. Fernandes, G., 2005. Behavior of Railway Pavement Structures Using Fine Soils and/or Iron Mining Waste Associated with Geosynthetics. Doctoral Thesis, University of Brasília, UnB, Brasília. 250p.
7. Luz, A. B. D., & Lins, F. A. F. (2018). Introdução ao tratamento de minérios. CETEM/MCTIC.
8. Marinho, F. A. & Vargas Jr. E. A. (2020). Effect of Suction on the Shear Strength of Soil–Rock Interfaces. Geotechnical and Geological Engineering, 38(6), 6145-6155.
9. Marinho, F. A. M., Carnero Guzman, G. G., & Orlando, P. Del G. (2016). Constant water content compression tests on unsaturated compacted soil with suction measurement using a HCT. International Journal of Geomechanics, 16(6), D4015008
10. Oliveira, O. M., Li, P., Marinho, F. A., & Vanapalli, S. K. (2016). Mechanical behaviour of a compacted residual soil of gneiss from Brazil under constant water content condition. Indian Geotechnical Journal, 46(3), 299-308.
11. Pereira, E. L., (2005). Potential Study of Liquefaction of Iron Ore Tailings under Statistical Loading. Master's Dissertation, Federal University of Ouro Preto. Graduate Program in Civil Engineering, Ouro Preto. 185p.
12. Rahardjo, H., Heng, O. B., & Choon, L. E. (2004). Shear strength of a compacted residual soil from consolidated drained and constant water content triaxial tests. Canadian Geotechnical Journal, 41(3), 421-436.
13. Sheng, D., Zhou, A., & Fredlund, D. G. (2011). Shear strength criteria for unsaturated soils. Geotechnical and Geological Engineering, 29(2), 145-159.
14. Silva, J. P. D. S., Cacciari, P. P., Torres, V. F. N., Ribeiro, L. F. M., & Assis, A. P. D. (2022). Behavioural analysis of iron ore tailings through critical state soil mechanics. Soils and Rocks, 45.
15. Thu, T. M., Rahardjo, H., & Leong, E. C. (2006). Shear strength and pore-water pressure characteristics during constant water content triaxial tests. Journal of Geotechnical and Geoenvironmental Engineering, 132(3), 411-419.
16. Uyeturk, C. E., & Huvaj, N. (2021). Constant water content direct shear testing of compacted residual soils. Bulletin of Engineering Geology and the Environment, 80(1), 691-703.
17. Vilar, O. M. (2006). A simplified procedure to estimate the shear strength envelope of unsaturated soils. Canadian Geotechnical Journal, 43(10), 1088-1095.
18. Vo, T., Yang, H., & Russell, A. R. (2016). Cohesion and suction induced hang-up in ore passes. International Journal of Rock Mechanics and Mining Sciences, 87, 113-128.