Proceedings of the 7th International Conference on Geotechnical and Geophysical Site Characterization
Barcelona, 18 - 21 June 2024

Geotechnical parameters of filtered tailings and waste rock from an Iron Quadrangle mining complex used in stacking projects.

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ABSTRACT

The complex where we used the materials ins this study, explores iron ore in an open pit process and is formed by a significant number of mines, and all their geotechnical structures such as waste rock stackings, tailings dams and, recently, the stackings that are being constructed with waste rock and tailings.

For the piles formed by the shared disposal of waste rocks and filtered tailings, the characterization of the materials and the strength and critical state parameters determined the executive methodology and the safety factors required for the projects.

The waste rocks and filtered tailings are mechanically disposed and divided into zones defined not only according to the geotechnical characteristics of the materials, but also the structural and operational needs of the stacking, which are divided into the confining zone and the confined zone.

In the confining zone, compacted waste is deposited. The aim of this procedure is to enhance the structural performance by employing materials with higher resistance. In the confining zone, as closer to the outer layer of the pile, greater shear strength is mobilized.

In the confined zone, friable waste, and mining tailings are disposed. In this zone, there is less mobilization of shear strength. For tailings, control and evaluation adhere to parameters outlined by the Critical State Line, employing the void ratio control of layers. This ensures dilatant mechanical behaviours for all confinement stresses specified in the project.

Keywords: tailings, waste rock, filtered tailings, stacking tailings

1. Introduction

The great challenge of Brazilian mining in recent years has been the development of technologies that allow tailings to be disposed without the use of dams, in line with a vision of greater safety for companies, society and the environment. With this vision of ESG (Environmental, Social and Governance), Brazilian mining companies have begun to study filtered tailings, for a safer disposal through filtered tailings piles.

1.1. Waste Rocks

Waste rock is the material generated in the mining process due to the superficial removal of rocks without the presence of the ores to be mined. The types of waste rock are therefore directly determined by the local geology. The mine complex is in the Iron Quadrangle region of Minas Gerais, Brazil, and thus has a rock formation originating from sedimentary and volcanic rocks which, through major shear deformations and the action of hydrothermal processes over millions of years, have been transformed into schists, gneisses and quartzites. Fig. 1 is a representation of a mining complex geological map, which shows the geological groups and subgroups where the rocks were formed.

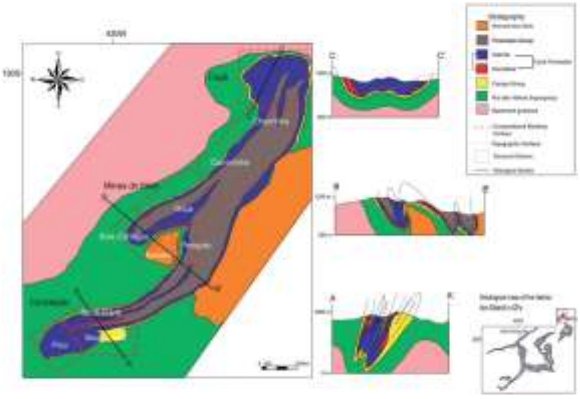

Figure 1. Geological map of the Mining Complex.

1.2. Filtered Tailings

The facilities that filter the tailings from the iron ore Plants inside the mining Complex are capable of filtering and processing approximately 54 million tons of tailings on a dry basis (filtrate) per year. The tailings pulp from the iron ore extraction process passes through cycloning and thickening stages, and is then densified and filtered, generating tailings with a geotechnical moisture content of approximately 14%, which is disposed in piles near the facilities, where trucks are loaded to transport the tailings to the filtered tailings stacking areas. In addition, the filtered liquid is reused as process water within the facilities, reducing the necessity of new water in the entire iron ore extraction process. Fig. 2 is an example of the tailings filtering process at the mining Complex.

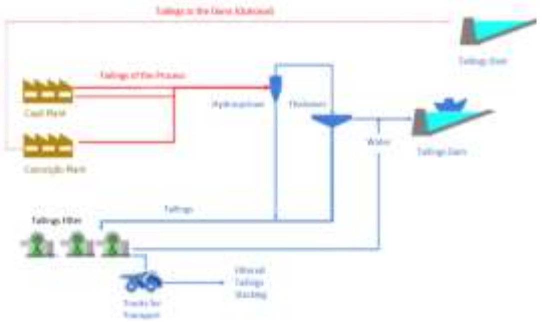

Figure 2. Tailings filter process.

2. Geomechanical analysis

For the geomechanical analysis of the waste rock, due to the great natural granulometric variation of the material coming from the rock matrix, it was decided to study the geomechanical parameters of the friable waste rock, which are the most conservative factors in a project analysis, since they have the lowest shear strength. Thus, a campaign of triaxial tests was carried out to determine the strength parameters of the aggregates. In addition, a complete characterization of these materials determined parameters such as grain size, liquidity and plasticity limits, specific gravity, maximum and minimum void ratio, permeability, and compaction.

The same tests were carried out on the tailing's samples coming directly from the filtered tailings piles, thus determining the parameters of the materials that are stacked and guiding the projects.

2.1. Waste rock tests results

A total of 11 different samples were collected from the various waste rocks piles in the mining complex in order to map the characteristics of all the waste rocks, and a summary of the results is presented here. "Table 1" lists the sample codes, predominant lithologies and the waste rock pile from which the samples were collected.

Table 1. Samples, lithology and local collected.

Sample	**Predominant Lithology**	**Sampling Site**
COR-P01	Schist	Correia waste rock pile
DIN-P01	Schist/Quartizite	Dinamitagem waste rock pile
MAN-P01	Schist	Mangueira waste rock pile
BOR-P01	Schist	Borrachudo Inferior waste rock pile
BOR-P02	Schist	Borrachudo Superior waste rock pile
CAN-P01	Schist	Canga waste rock pile
CAN-P02	Schist	Canga waste rock pile
CON-P01	Schist/Quartizite	Convap waste rock pile
IPO-P01	Gneiss/Schist	Ipoema waste rock pile
MAR-P01	Schist	Maravilha waste rock pile
BAN-P01	Schist/Quartizite	Bangalô waste rock pile

2.1.1. Physical, compaction and permeability characterization

The characterization of the samples demonstrated that the specific gravity of the samples did not change much, ranging from 2.67 g/cm³ to 3.07 g/cm³, with an average value of 2.85 g/cm³.

The samples had a plasticity index varying between 8 and 20 and an average of 16.6, which according to Burmister (1949) is characteristic of materials with medium plasticity. With the exception of sample MAR-P01, all the tests showed a plasticity index above 10. The plasticity chart of the tests on the tailings of the mining Complex is shown in Fig. 3 and the values of liquidity limit, plasticity limit and plasticity index in "Table 2".

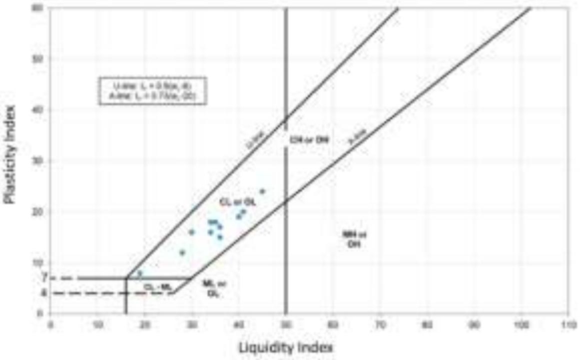

Figure 3. Plasticity Chart.

Table 2. LL, PL, PI by sample

Sample	**Plasticity**		
	LL	**PL**	**PI**
BAN-P01	34	16	18
BOR-P01	36	21	15
BOR-P02	35	16	18
CAN-P01	28	16	12
CAN-P02	40	21	19
CON-P01	36	20	17
COR-P01	45	22	24
DIN-P01	41	21	20
IPO-P01	34	18	16
MAN-P01	30	14	16
MAR-P01	19	11	8

As the samples were taken from areas of the existing waste rock piles with higher concentrations of friable waste materials, the samples did not show significant fractions of boulders, with the exception of sample MAN-P01, which had a significant content of materials with larger grain sizes. In general, the samples showed little variation in D50, with the average clay content being close to 7.8%, silt at 42% and sand at 47%. All the particle size characterization tests were carried out in accordance with the Brazilian standard ABNT NBR 7181. Fig. 4 shows the particle size curves of all the waste rocks samples tested and “Table 3” shows the percentages of clay, silt, sand, and gravel in each sample tested, in accordance with the Brazilian standard.

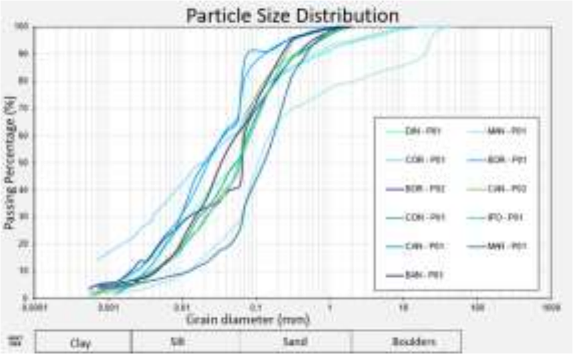

Figure 4. Waste rock particle Size.

Table 3. Clay, Silt, Sand and Boulders percentage

Sample	**Granulometry**			
	Clay (%)	**Silt (%)**	**Sand (%)**	**Boulders (%)**
BAN-P01	7	55	38	0
BOR-P01	9	59	33	0
BOR-P02	11	31	58	0
CAN-P01	5	43	52	0
CAN-P02	5	62	33	0
CON-P01	5	47	48	0
COR-P01	22	41	32	6
DIN-P01	9	43	44	5
IPO-P01	6	44	50	0
MAN-P01	2	26	52	20
MAR-P01	5	21	74	0

Minimum and maximum void ratio tests were carried out, indicating an average minimum value of 0.884 and an average maximum value of 1.244.

Proctor compaction tests at normal energy indicate maximum dry density (ρd) values varying between 1.58 g/cm³ and 2.13 g/cm³, with an average value of 1.7 g/cm³, associated with an average optimum moisture content (w_{ot}) of 18.40%. However, there is variability in the values found for the optimum humidity of the waste rocks, due to the different lithologies studied.

“Table 4” shows the maximum dry density and optimum moisture values of the waste rock found in the compaction tests.

Table 4. Compaction tests results

Sample	**Compaction**	
	w (%)	**ρdmax (g/cm³)**
BAN-P01	18,7	1,72
BOR-P01	23,6	1,64
BOR-P02	20,6	1,76
CAN-P01	17,2	1,87
CAN-P02	20,9	1,73
CON-P01	16,1	1,74
COR-P01	15,4	1,95
DIN-P01	19,6	1,75
IPO-P01	16,2	1,63
MAN-P01	21,1	1,58
MAR-P01	12,5	2,13

To determine the permeability of the tailings, drilling campaigns were carried out on the piles where the materials were collected for the laboratory characterization tests, with infiltration tests in the field. These tests demonstrate the permeability of the materials when stacked and thus represent the conditions to which the waste rock in the shared tailings and waste rock disposal piles will be subjected.

Most of the tests showed results in the $1x10^{-6}$ m/s to $1x10^{-8}$ m/s range, with an average value of $1.23x10^{-7}$ m/s. Fig. 5 illustrates the permeability of the tailings in various boreholes from the drilling campaign in the piles and at different depths. The test in borehole SRIPDE-06 shows a much lower permeability than the others, probably because it was drilled in compacted clay material.

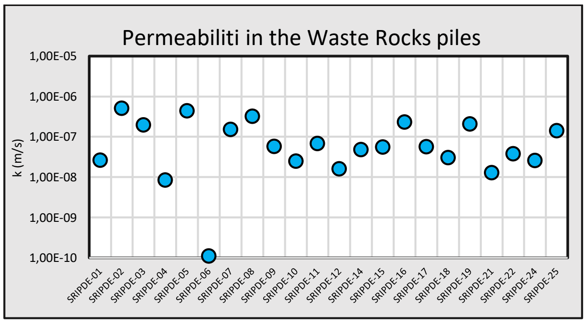

Figure 5. Permeability results in the drilling campaign.

2.1.2. Triaxial tests results

Triaxial tests of the undrained (CIU) and drained (CID) types were carried out on several different specimens. Due to the great variation in the granulometry of the materials, the samples were taken from sites with friable waste. These samples were molded in the laboratory with a degree of compaction of 85% of Normal Proctor, in order to provide a conservative densification condition.

The rupture points in the tests were identified for the maximum deformation criterion, in the plane of the deviation stresses (q) and the average effective stresses (p'), based on the critical state theory. This analysis methodology is justified by the high confining stresses to which the waste rock near the foundation will be subjected at the end of the piling. Fig. 6 shows the trajectories of the tests carried out on the materials considered to have the worst resistance, namely the lithology considered to be friable schist and gneiss.

Figure 6. Triaxial results

Using the methodology of Jefferies and Been (2016), for materials subjected to compression, were defined the friction angle in the critical state (φ'r) and the slope of the line of best adjustment of the points of maximum deformation in space (p',q). Equation 1 was used to determine the line of best adjustment (Mtc).

$$\mathrm{M_{tc}} = \frac{6\cdot\mathrm{sen}\ \varphi_r'}{3-\mathrm{sen}\ \varphi_r'} \qquad (1)$$

"Table 5" shows the values of these parameters obtained for schist and gneiss, and the adjusted R^2 of the results for each lithology separately.

Table 5. Parameters obtained.

Sample	**R²**	**Mtc**	**φ'r (°)**
Gneiss	0,9914	0,9803	24,91
Friable Schist	0,9306	0,9306	23,75

The deformability parameters were determined using drained triaxial tests, which allow for greater deformation of the specimen. The modulus of deformability was defined for 50% of the mobilization of the maximum deviatoric stress at each confining stress. The results are shown in Fig. 7, which plots the modulus of elasticity for each confining stress. It can be seen that, in general, the samples show a considerable increase in strength as a result of the increase in the confining stress.

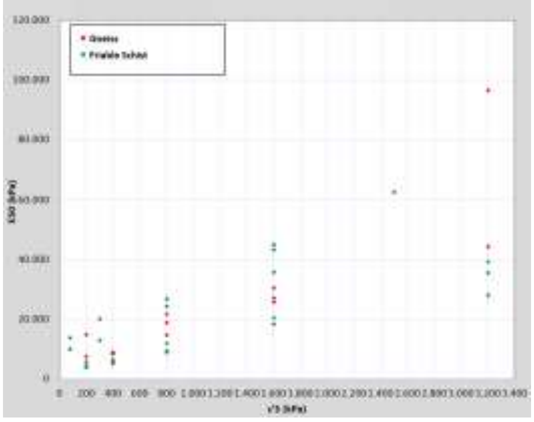

Figure 7. Deformability in the friable waste rocks

2.2. Tailings tests results

The filtered tailings from the mining Complex plants have a characteristic proportion of 80% of the composition of the tailings being classified as sandy, and 20% of the mass being considered ultrafine. This material, called Total Tailings, is made up of a mixture of 100% of the volume generated in the thickener and the flotation tailings generated after passing through the hydrocyclone.

2.2.1. Physical, compaction and permeability characterization

The characterization studies of the filtered tailings for the piling projects were carried out by two different laboratories, one Brazilian and the other European.

The tests to determine the Atterberg limits defined this material as non-plastic. Fig. 8 shows the particle size curves of the tests carried out. It can be seen that the granulometry of the material is made up of 41% to 70% sand, 27% to 48% silt and 2% to 8% clay, thus demonstrating the wide variation in the granulometry of the tailings, due in part to the natural variations in the mining areas and due the extraction ore process. "Table 6" shows the percentages of each material in the characterization tests. Two samples were tested after performing drained and undrained triaxial tests at stresses of 1600kPa, in order to check for possible grain breakage.

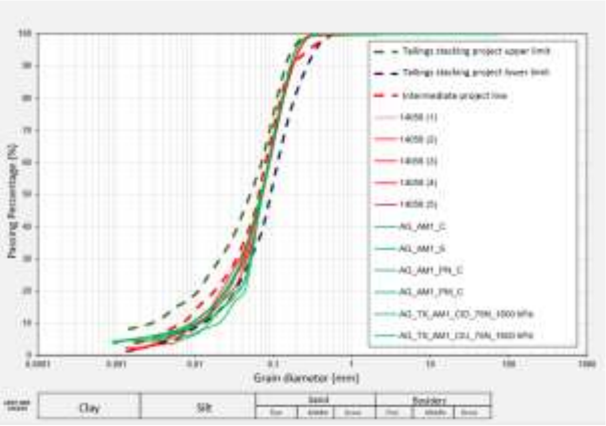

Figure 8. Tailings particle size.

Table 6. Clay, Silt, Sand and Boulders percentage

Sample	**Granulometry**			
	Sand (%)	**Sand (%)**	**Sand (%)**	**Sand (%)**
14058 (1)	2,4	39,9	49,1	8,4
14058 (2)	2,4	41,1	47,5	8,6
14058 (3)	2,4	39,8	48,6	9
14058 (4)	2,4	41	47,8	8,6
14058 (5)	2	37,3	51,8	8,7
AG_AM1_C	5	40	50	5
AG_AM1_S	5	35	55	5
AG_AM1_PN_C	5	37	58	0
AG_AM1_PM_C	5	27	63	5
AG_TX_AM1_CID_75N_1600 kPa	5	37	53	5
AG_TX_AM1_CIU_75N_1600 kPa	5	38	55	2

The specific gravity of the samples did not vary greatly between the laboratories, ranging from 2.97 g/cm³ to 2.99 g/cm³ in the samples tested in the Brazilian laboratory and with an average value of 3.05 g/cm³ in the European laboratory.

The average maximum and minimum void ratio of the total filtered tailings is 0.93 and 0.61, respectively. These tests were only carried out on the samples that were sent to the Brazilian laboratory.

“Table 7” shows a summary of the Normal Proctor compaction tests carried out on the total filtered tailings. Tests were carried out on the 5 samples from the Brazilian laboratory and only one test on a sample from the European laboratory. The maximum dry density ranged from 1.91 g/cm³ to 2.00 g/cm³. The optimum humidity ranged from 12.00% to 13.30%.

Table 7. Tailings compaction tests results

Sample	**Compaction**	
	w (%)	**ρdmax (g/cm³)**
14058 (1)	13,30	1,91
14058 (2)	12,60	1,97
14058 (3)	13,00	1,90
14058 (4)	12,00	2,00
14058 (5)	12,60	1,95
AM1_PN	11,50	1,97

The permeability tests were carried out on samples molded in the laboratory with different degrees of compaction during normal energy Proctor tests. These tests were carried out in the Brazilian laboratory. In this study, the degree of compaction ranged from 70% to 98%. “Table 8” summarizes the results of these tests.

Table 8. Permeability results

Tailings		**Permeability**
Sample	**Compaction**	**k (m/s)**
14058 (1)	70%	3,17E-07
14058 (2)	80%	2,92E-07
14058 (3)	90%	9,49E-08
14058 (4)	95%	9,39E-08
14058 (5)	98%	4,18E-08

2.2.2. Triaxial tests results

In order to define the shear strength parameters of the filtered tailings, as well as the waste rocks, the Critical State theory defined by Jefferies and Been (2016) was adopted. Several triaxial tests were carried out on filtered tailings samples molded at different initial void ratios, in order to determine the critical state line (CSL) of the tailings. Drained and undrained tests were carried out, in dense and loose molding conditions, in a range of stresses varying from 75 kPa to 6400 kPa. In all tests, the results of the void ratios before and after shear, deviation stresses and average effective stresses after shear and peak values were monitored.

With the void ratio and effective stress at the end of the shear, a graph was developed correlating the variations of the void ratios in the test phases with the effective stresses to obtain the critical state line (CSL) of the tailings, as shown in Fig. 9. The determination of the CSL took into account all the tests carried out, but with a greater focus on the results of the tests at stresses of 100 kPa to 2,000 kPa, since this is the stress range of the piling projects. Stress paths below 100 kPa indicate a change in the inclination of the CSL, a phenomenon that occurs for small values of effective stress, as presented by Jefferies and Been (2016).

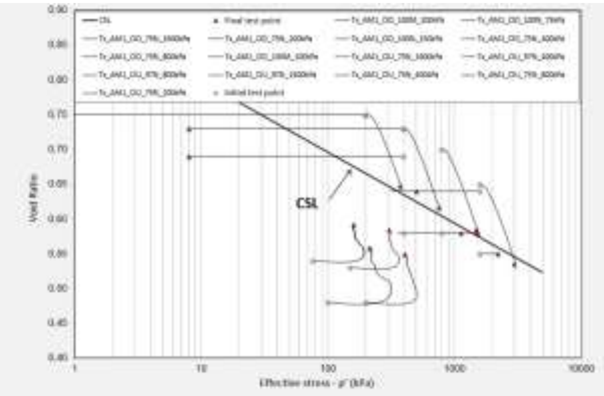

Figure 9. Tailings CSL

The definition of the friction angle in the critical state (φ'r) was carried out according to the methodology presented by Jefferies and Been (2016) and mentioned in equation 1 above. To determine the friction angle in the critical state, the inclination of the line of best adjustment of the points of maximum deformation (Mtc,) can be used.

In all the tests carried out, the values for minimum dilatancy (D_{min}) and the stress ratio at minimum dilatancy were obtained. With these values, the graph shown in Fig. 10 was defined, and the inclination of the best adjustment line was obtained. For a value of Mtc equals to1.40, the result is φ'r is 34.6°.

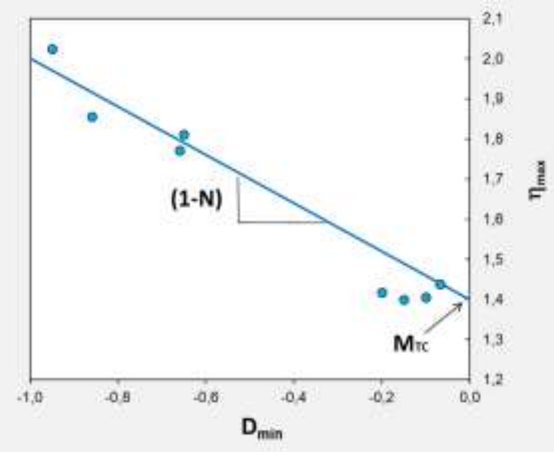

Figure 10. Graphic η_{max} x D_{min}

A classification of the behavior of the samples proposed an analysis of the material considering the tests as contractile, contractile-dilatant and dilatant, where contractile behavior was attributed to tests in which there was positive pore-pressure generation or a decrease in shear volume. Dilatant behavior was attributed to tests in which negative pore pressure was generated or shear volume increased. Contractile-dilatant behavior was attributed to tests that showed contractile behavior at the beginning and began to show dilatant behavior during the shear stage. The result was that samples with a void ratio close to the minimum showed dilatant behavior at all stresses. Samples with higher void ratios showed contractile behavior at lower stresses and contractile-dilatant behavior at higher stresses, above 1600 kPa.

Tests with high deformation rates of the filtered tailings were carried out to determine the strength parameters. An evaluation of the tests with minimum void ratios, in order to achieve a dilatant condition of the stacked tailings, was carried out to determine the strength parameters expected after compaction of the tailings. Fig. 11 shows the rupture envelopes of the samples tested.

“Table 9” shows the parameters obtained for each envelope.

Table 9. Resistance parameters.

Triaxial Test emin	**Interpretation**	**c' (kPa)**	**ϕ' (°)**
CIU	Maximum obliquity.	10,0	35,7
	Maximum deviator (peak envelopes)	0,0	35,9
	Critical State	0,0	35,9
CID	Maximum obliquity	13,7	36,7
	Maximum deviator (peak envelopes)	13,7	36,3
	Critical State	0,0	36,2

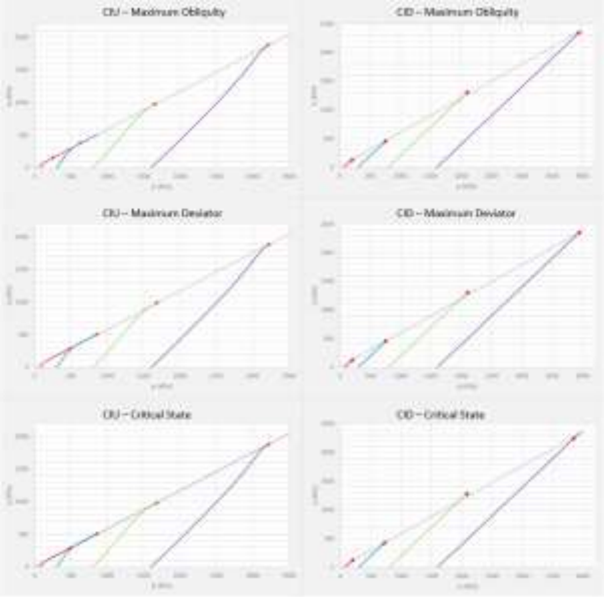

Figure 11. Rupture envelopes with e_{min}

3. Conclusions

There is a linearity in the parameters of the angle of resistance in the critical state, demonstrated in the calculations according to the studies by Jefferies and Been (2016) with the results of the high deformation tests with minimum void ratios. This indicates that tailings compacted to a 98% degree of compaction in Proctor with normal energy are nearing their minimum void ratio, suggesting that under these conditions, the tailings exhibit dilatant behavior with high resistance.

When comparing the results of the resistance parameters of the friable waste rocks with the tailings, the friable waste rocks have a lower critical friction angle. This shows that friable waste rocks have lower shear strength than compacted tailings. However, it should be noted that blocky tailings with high rock characteristics, which were not studied in this project, naturally have higher resistance parameters, and these materials have higher shear strength when compared to tailings.

The results of the triaxial tests show that segregation of materials in shared tailings and waste rocks piles may be necessary to increase the safety factor of the structures.

Due to the plasticity of waste rocks, these materials have lower permeability than non-plastic tailings. The ability of waste rocks to resist erosive processes means that these materials can be used in exposed areas such as berms and slopes and can be used to close and protect piles. Due to the high rainfall in tropical locations, such as the Iron Quadrangle region, this has been a highly relevant study.

In the particle size characterization tests on the tailings after shearing at confining stresses of 1600 kPa, no particle breakage was observed, demonstrating the high resistance of the iron ore tailings particles.

In order to control the critical state, and thus the susceptibility to liquefaction of the tailings, the determination of the CSL of this material was essential to condition the void ratio to which the tailings should be in the pile, and the degree of compaction, for the operation with the minimum safety factors of the piles.

Acknowledgements

The authors are grateful for the financial support provided by the Vale S.A. company. The viability of studies on tailings and waste rocks is essential for the company, and for the entire of Brazilian mining industry.

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