

GEOTECHNICAL BEHAVIOR OF GOLD ORE TAILINGS FROM A FILTERED STACK IN MINAS GERAIS, BRAZIL

Mayara Ferreira Rodrigues¹, Márcio de Souza Soares de Almeida¹, Marcos Barreto de Mendonça¹ and Jaime Pinheiro²

¹Federal University of Rio de Janeiro – UFRJ; ²AngloGold Ashanti USA

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ABSTRACT

Catastrophic events related to tailings dams worldwide —notably in Brazil— have brought about the need to expand geotechnical studies on tailings disposal. Special attention should be given to mechanically compacted filtered tailings due to the significant increase in the height of such deposits, making it necessary to better understand the mechanical behavior of these structures. This paper compiles and discusses the results of field and laboratory tests on filtered gold ore tailings from an experimental embankment and a tailings stack currently operated by a mining company in Minas Gerais, Brazil. The tailings originate from the flotation stage, part of the metallurgical process of gold ore beneficiation. In-situ density tests were carried out to understand the effect of the compaction process across different layer thicknesses using various equipment types, and laboratory tests were conducted to obtain the characterization, compaction, shear strength, and hydraulic conductivity parameters of the material. Field tests demonstrated the need to restrict layer thicknesses to 30 cm and allowed for the discussion of compaction quality issues as a function of the equipment used. Based on the index test results, the material was classified as non-plastic sandy silt. The hydraulic conductivity tests on trimmed or laboratory-compacted specimens at different void ratios indicated virtually isotropic behavior. Triaxial compression results, in which specimens reached the critical state, revealed four distinct critical state lines (CSLs), a phenomenon attributed to grain size variations observed in the samples. The results highlight the need to monitor variations in the geotechnical characteristics of tailings over the stacks service life to adjust construction processes accordingly.

1. INTRODUCTION

Among the available options, the use of filtered tailings compacted in stacks has been widely considered a viable Tailings Storage Facility (TSF) option (Davies, 2011; Crystal et al., 2018; Ulrich, 2019; Cacciuttolo & Campomanes, 2022; Cacciuttolo and Atencio, 2023).

Fourie et al. (2022) highlight the continuous growth of global mining activities and the reduced content of the extracted ore, resulting in increased tailings production. These conditions underscore the importance of improving the understanding of the geotechnical behavior of these materials, enabling the improvement of the disposal of filtered tailings in stacks and contributing to process efficiency, in order to create better technical basis for projects and safer structures (Davies, 2011; Gomes et al., 2019; Furnell et al., 2022).

As mining production continues to grow, filtered stacks have grown increasingly larger in height and volume (Crystal et al., 2018; Fourie et al., 2022; Cacciuttolo and Atencio, 2023). In these structures, the filtered tailings are transported by trucks or conveyors. They are then deposited and spread, homogenized using a tillage tractor until the optimum moisture content is reached, and subsequently compacted in layers of predefined thicknesses. At the end of each cycle, geotechnical quality control tests are conducted, and the process is repeated, resulting in a partially saturated structure with sufficient in-situ density and geometry, thereby eliminating the need for auxiliary containment structures (Davies, 2011; Cacciuttolo & Campomanes, 2022). Therefore, conducting studies on test embankments to obtain geotechnical parameters and assess the behavior of specific tailings when mechanically compacted after filtration is an essential step. Design requirements must also consider climatic challenges, regional seismicity, logistical constraints, operational scale, and availability of construction equipment (Davies, 2011).

Furthermore, defining geotechnical parameters based on laboratory tests is paramount in guiding the design and operational criteria of these structures (Davies, 2011; Crystal et al., 2018). These experimental campaigns have continuously evolved to reduce uncertainties arising from the unique characteristics of tailings (Fourie et al., 2022; Delgado et al., 2023). The behavior

of tailings must be analyzed within the framework of Critical State Soil Mechanics (CSSM), as the void ratio of compacted tailings and the stress conditions to which they are subjected directly influence their shear strength (*Jefferies and Been, 2016*). This context serves as the motivation for this study, which presents and discusses the results of an experimental campaign on filtered gold ore tailings from the flotation stage of a project in Minas Gerais State, Brazil, involving both field and laboratory tests. Field tests were conducted on an experimental embankment and a filtered tailings stack under different compaction conditions. Laboratory tests for characterization, hydraulic conductivity, and stress-strain behavior were carried out on specimens trimmed from undisturbed blocks, as well as on laboratory-compacted specimens obtained from samples collected from both structures.

2. MATERIALS AND METHODS

2.1 TAILINGS STUDIED

The tailings analyzed in this study originated from the flotation stage of the gold ore beneficiation process at an underground mine in the *Quadrilátero Ferrífero* - State of Minas Gerais, southeastern Brazil. The material was transported by truck from the filtration plant and deposited at both a tailings stack and an experimental embankment. Upon exiting the filtration plant, the tailings had a moisture content ranging from 17.4% to 24.1%.

To evaluate the behavior of the tailings under different compaction methods, data were collected from an experimental embankment with an approximate volume of 3,000 m³, constructed with 30 cm and 50 cm thick layers compacted using a track dozer, and from a tailings stack with a volume of approximately 160,000 m³, built with 30 cm thick layers compacted with a smooth drum roller without vibration.

Since the moisture content of the tailings exceeded the optimum range (12.7% to 17.4% — see section 3.2) upon leaving the filtration plant, the material was homogenized after placement using a tillage tractor to bring the material to the optimum moisture content. The layers were then leveled with a motor grader and compacted using the respective equipment.

2.2 SAMPLING AND EXPERIMENTAL CAMPAIGN

The tests were conducted in accordance with standards established by the American Society for Testing and Materials (ASTM). Field tests were performed on all layers of the experimental embankment and the filtered tailings stack to verify in situ density and moisture content. In-situ density measurements were taken on the top and bottom surfaces of all 50 cm thick layers and on selected 30 cm thick layers to evaluate variations in the degree of compaction (DC) between the two horizons. A total of 76 tests were conducted on the experimental embankment and 107 on the filtered tailings stack.

Disturbed samples from both structures were collected for laboratory characterization and compaction testing. Test specimens were then compacted in the laboratory at various void ratios to assess shear strength and hydraulic conductivity. Additionally, twelve undisturbed block samples were collected from which test specimens were trimmed for shear strength and hydraulic conductivity testing. The testing campaign is summarized in Table 1.

Table 1. Field and laboratory testing campaign.

Test	Qty.	Specifications
In-situ density	183	Hilf method
Grain size distribution: sieving and sedimentation; and particle specific gravity	29	-
Maximum and minimum void ratio	7	-
Standard Proctor compaction	59	Proctor standard energy
Falling-head permeability	24	Test specimens trimmed from undisturbed blocks or laboratory-compacted
CIU _{sat} triaxial compression	80 specimens	B Parameter ≥ 95%; p'_0 from 100 kPa to 1600 kPa. Test specimens trimmed from undisturbed blocks or laboratory compacted. Dimensions: h=110mm and D=50mm.
CID _{sat} triaxial compression	44 specimens	

Regarding the triaxial compression tests, volume variation was tracked throughout all stages, so that the void ratio at the end of shearing could be estimated with sufficient accuracy. Advanced laboratory techniques (*Jefferies & Been (2016); Viana da Fonseca et al., 2021*) such as lubricated ends, top-cap guided ram connections and the freezing method at end of shearing

were not employed in this study, as the scale of the experimental campaign and industrial requirements necessitated the use of a conventional test setup.

The behavior of the tailings was analyzed from the perspective of CSSM, by determining the Critical State Line (CSL) of the material (Jefferies & Been, 2016). Only the tests that actually reached the critical state condition (i.e., a final condition marked by no further variation in shear strength, volume or pore pressure generation) were used to assess the CSL.

The critical state void ratio was obtained at the end of the specimen compaction step since the tests were carried out with volume change control throughout all phases.

3. RESULTS AND DISCUSSIONS

3.1 FIELD TESTING

3.1.1 Degree of compaction and in-situ moisture content of tailings embankments

The in-situ density test results from the experimental embankment and the filtered tailings stack are presented according to the compaction cycles and equipment used. In studies on gold ore tailings, Zorzal *et al.* (2020) suggest obtaining a degree of compaction (DC) greater than 96% to ensure dilative behavior. Although this reference may vary according to the characteristics of different tailings, this observation is considered when analyzing the degree of compaction results from the field tests.

The DC verification test results were grouped according to the compaction equipment used (track dozer and non-vibratory smooth drum roller), layer thickness (30 cm and 50 cm), number of cycles (up to three, four, five and six cycles) and in-situ test position (top and bottom of the layer) – see Figures 1 and 2. For compaction using a smooth drum roller, only the middle of the layer was tested. Each compaction cycle corresponds to two passes of the compaction equipment.

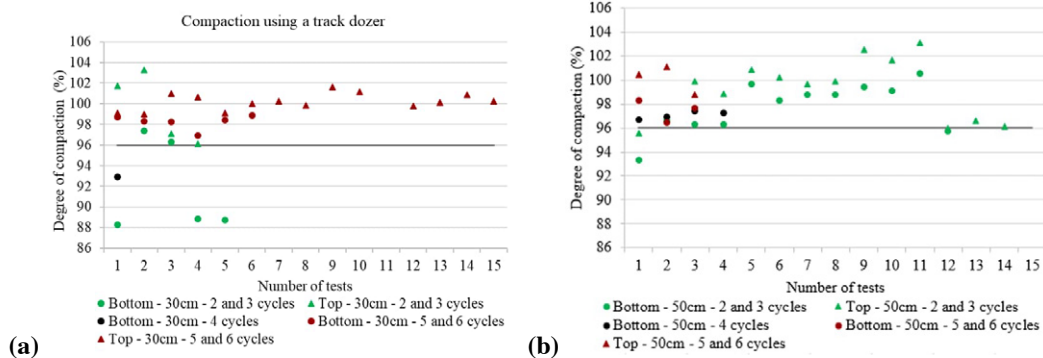


Figure 1. Degree of compaction at the top and bottom of layers compacted using a track dozer: (a) 30 cm-thick layer; (b) 50 cm-thick layer.

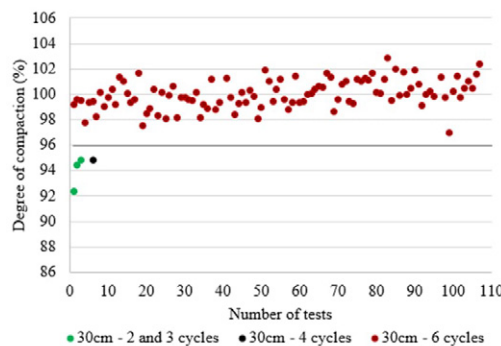


Figure 2. Degree of compaction in the middle of 30 cm-thick layers compacted using a non-vibrating smooth drum roller without vibration.

Based on the analysis of the results presented in Figures 1 and 2, the following observations were made:

- 30 cm-thick layer embankment compacted using a track dozer (Figure 1a):
 - The degree of compaction (DC) varied between the top and bottom surfaces, regardless of the number of compaction cycles applied. This variation reached up to 3% for five and six cycles and 13% for two and three cycles.
 - With two or three compaction cycles, the DC was concentrated above 95%. In contrast, with five or six cycles, it remained above 98%, at both the top and bottom surfaces, indicating a gain in DC as the number of compaction cycles increased.
 - The difference in DC between the top and bottom surfaces decreased as the number of compaction cycles increased, indicating greater homogeneity in compaction. Only one test was conducted at the base of the layer using four compaction cycles. As this test is not representative, no reliable conclusions can be drawn from this result.
- 50 cm-thick layer embankment compacted using a track dozer (Figure 1b):
 - For five and six compaction cycles, the DC of the top and bottom layers remained close to 98%. For fewer cycles, the results were more scattered, ranging from 93% to 103%.
 - The top layer results for two and three compaction cycles — higher than those obtained for five and six cycles — suggest that only the areas directly compacted by the track dozer were tested. The *USACE (1995)* notes this type of compaction heterogeneity when track dozers are used, which will be discussed later.
 - The DC varied between the top and bottom layers regardless of the number of compaction cycles, similar to the behavior observed in the 30 cm-thick layers.
 - The DC difference between the top and bottom layers was 5% for five and six cycles, and 3% for two and three cycles. With the increase in layer thickness, lower DC levels and greater scatter than those observed for the 30 cm-thick layer were expected; however, this was not observed. This result may also reflect the heterogeneity of the embankment material, as previously mentioned.
 - For four compaction cycles, an increase in DC was observed at the bottom of the layer compared to two and three cycles.
- 30 cm-thick layer embankment compacted using a non-vibrating smooth drum roller (Figure 2):
 - The use of six compaction cycles ensured an average DC close to 100%.
 - After two and three compaction cycles, the DC was lower than 95%. The lowest value observed was 92%, indicating the highest dispersion in results.
 - Four compaction cycles were insufficient to achieve DC values greater than 95%.
 - The DC tended to increase with the number of compaction cycles.

Figure 3 presents the average test results obtained under varying conditions of layer thickness, compaction equipment type, and test position, grouped according to the number of compaction cycles.

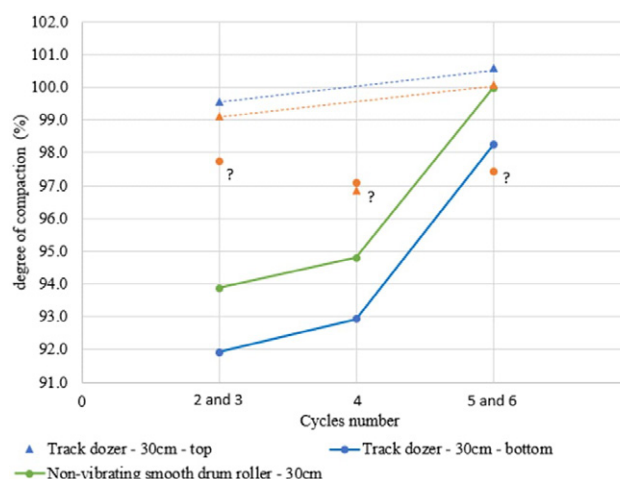


Figure 3. Average degree of compaction (DC) versus number of compaction cycles.

The analysis of the average results presented in Figure 3 led to the following conclusions:

- The DC tended to improve under all compaction conditions as the number of cycles increased.
- The dispersion of the average results decreased as the number of compaction cycles increased. For track dozer compaction on 30 cm-thick layers, the difference between top and bottom DC values was nearly 8% with two and three cycles and decreased to 3% with five and six cycles. This indicates that additional compaction cycles contributed to reduced layer heterogeneity.
- The increase in DC at the bottom of the layers was more significant when five and six compaction cycles were used.
- The use of up to four compaction cycles resulted in average DC values below 95%.
- The tests on 50 cm-thick layers exhibited behavior different from that described above. This may suggest that the tested areas were better compacted than those selected for the 30 cm-thick layer embankment, highlighting the heterogeneity of tailings compacted by track dozers. This variation may result from uneven coverage by the track dozer, as the entire surface may not have received the same number of passes. This is due to the need for precise lateral displacement of the dozer, given the gap between its tracks – a condition does not present with the smooth drum roller.

Crystal et al. (2018) and *Wilson (2021)* emphasize that adequate compaction of tailings reduces the stack's susceptibility to liquefaction, promotes dilative behavior in embankments, and requires care to avoid the formation of loose zones within the structure. In this context, based on observations of layers compacted using a track dozer, the *USACE (1995)* states that the number of compaction cycles in embankments compacted with a track dozer cannot be defined in the same way as for tamping rollers. This is due to the spacing between the equipment's tracks, which prevents the entire area corresponding to the dozer's width from being fully compacted. This operational limitation highlights the potential heterogeneity of the embankment if technical specifications and field monitoring do not ensure that the lateral displacement of the equipment adequately covers the entire surface under consistent compaction conditions.

According to *USACE (1995)*, in soils with low fines content and high permeability — i.e., sandy soils — the layer thickness should be limited to 40 cm, and in materials with higher fines content, to 20 cm. *Cacciuttolo & Campamones (2022)* recommend limiting the layer thickness to 30 cm for tailings. Since the tailings under study have a sandy silt composition, the *USACE (1995)* indicates that 50 cm-thick layers are not suitable for building embankments with this type of material. This is supported by the analysis of the test results, where the DC of the 30 cm-thick layers remained above 98% for five or six compaction cycles (Figure 1a and Figure 2). *Wagner et al. (2023)* emphasize that, although there is interest in increasing layer thicknesses to improve productivity, thinner layers promote higher degrees of compaction, directly affecting the geotechnical behavior of the structure.

3.2 LABORATORY TESTING

3.2.1 Characterization and Compaction

Based on the results of geotechnical characterization and compaction tests, the tailings were classified as sandy silt according to grain size analysis, and as a low-plasticity silt (ML) according to the Unified Soil Classification System (USCS) (*ASTM D2487, 2017*). The particle size distribution was as follows: clay content ranging from 0 to 6.5%, silt from 49% to 69.5%, and sand from 24% to 50.3%. The material was non-plastic, with specific gravity values ranging from 2.791 to 2.940 g/cm³, maximum dry density ranging from 1.679 to 1.806 g/cm³, and optimum moisture content ranging from 14.6% to 18.8%. Figure 4 shows the grain size distribution of the tailings studied, which is consistent with grain size distribution curves for gold ore tailings from various locations.

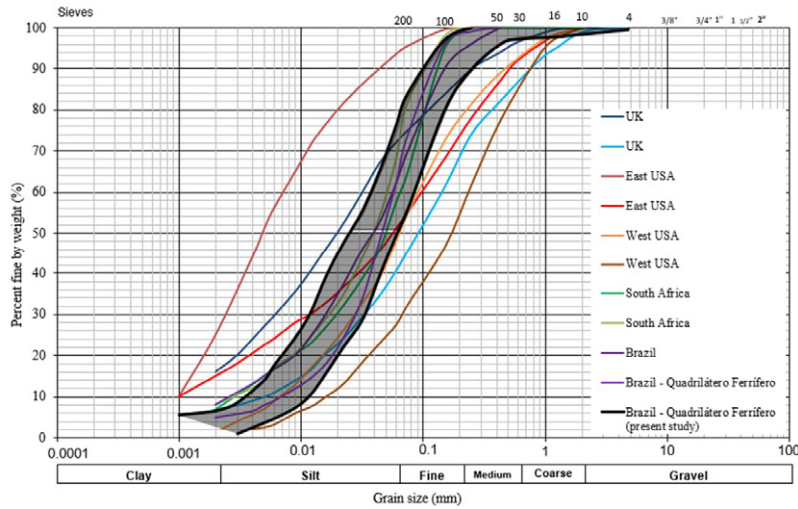


Figure 4. Comparison between the grain size distribution of the analyzed tailings and the grain size distribution curves of gold tailings presented by other authors (adapted from Vick, 1990, and Bedin, 2010).

Figure 5.a presents the Standard Proctor compaction curves obtained for each sample, as well as the average curve of all compaction tests, regardless of the dispersion among the individual curves. The dispersion of the compaction curves indicates heterogeneity among the samples. No clear correlation could be established between the variability of the compaction curves and the grain size distribution or physical properties of the tailings. Figures 5.b and 5b present the graphs showing the distribution of the obtained values of maximum dry density and optimum moisture content. The average maximum dry density of 1.763 g/cm³ and the average optimum moisture content of 16.5% are within the range reported in the literature (Bedin, 2010; Preciado et al., 2014; Zorzal et al., 2020; Oliveira et al., 2024), i.e., from 1.679 g/cm³ to 1.806 g/cm³.

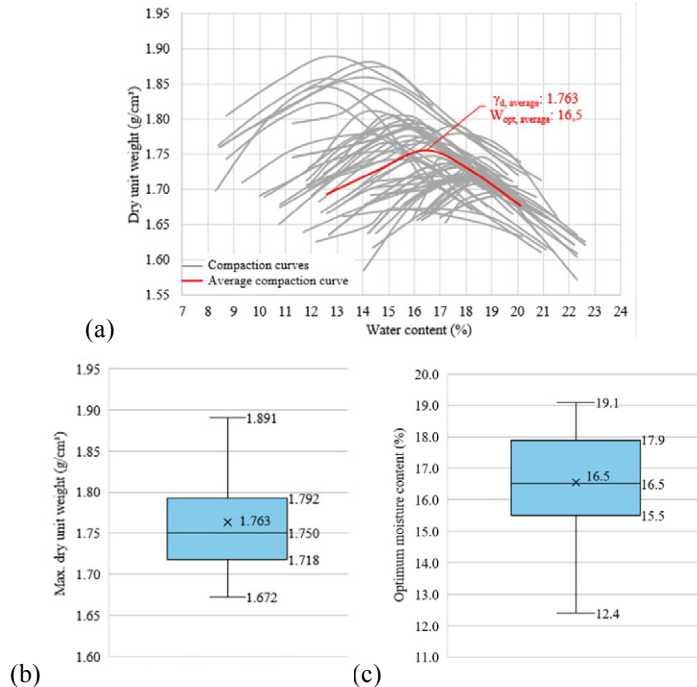


Figure 5. (a) Standard Proctor compaction curves, (b) Distribution of maximum dry density results, (c) Distribution of optimum moisture content results.

The tailings' minimum void ratio (e_{min}) ranged from 0.7 to 0.9, while the maximum void ratio (e_{max}) ranged from 1.21 to 1.40. The average values were $e_{min} = 0.783$ and $e_{max} = 1.274$, lying within the ranges observed by *Zorzal et al. (2020)* ($e_{min} = 0.7$ and $e_{max} = 1.25$) and *Oliveira et al. (2024)*, ($e_{min} = 0.56$ and $e_{max} = 1.44$), both referring to gold ore tailings in Brazil.

3.2.2 Hydraulic conductivity of the tailings

Tests were performed on specimens vertically and horizontally trimmed from undisturbed block samples collected from the experimental embankments and the tailings stack, as well as on laboratory-compacted specimens at different void ratios. The results were used to calculate the vertical (k_v) and horizontal (k_h) hydraulic conductivity of the tailings. The hydraulic conductivity ranged from 5×10^{-6} cm/s to 1.3×10^{-4} cm/s, with an average of 6.2×10^{-5} cm/s. As the void ratio decreased, there was a tendency for the hydraulic conductivity to reduce (Figure 6).

Analysis of the results from specimens trimmed in both directions (vertical and horizontal) from undisturbed samples collected in the experimental embankment and the tailings stack indicated very low anisotropy (k_h/k_v), with values between 0.6 and 1.5 — suggestion, in practical terms, that the material behaves isotropically. For this reason, anisotropy is not differentiated in the graph presented in Figure 6.

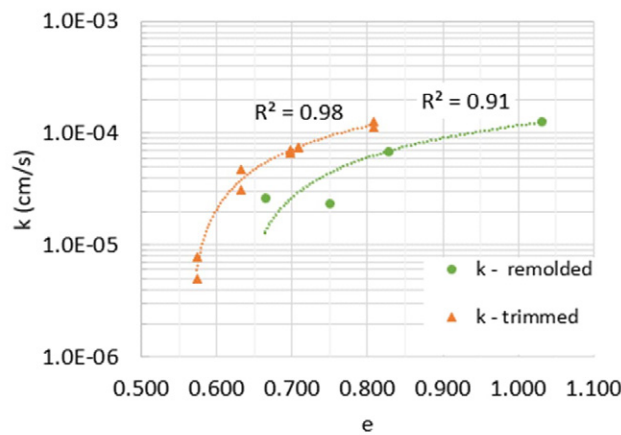


Figure 6. Hydraulic conductivity obtained.

Vick (1990) presented a study that included hydraulic conductivity tests on mine tailings with fines content greater than 30% and non-plastic or low-plasticity tailings. The results indicated hydraulic conductivity values ranging from 10^{-2} cm/s to 10^{-7} cm/s. The fines content and the non-plastic behavior of the filtered tailings analyzed in this study are consistent with the characteristics of the materials studied by *Vick (1990)* and fall within the same range of hydraulic conductivity.

The hydraulic conductivity values obtained fall within the typical range for various silt-sized mine tailings (1×10^{-4} to 1×10^{-6} m/s), as compiled by *Dias Neto et al. (2024)*. The values found here are also close to those presented by *Qiu & Segó (2001)*— 2.7×10^{-5} to 6.7×10^{-5} cm/s — for gold tailings containing 81.3% fines ($< 75 \mu\text{m}$), classified as ML by the USCS (*ASTM D-2487, 2017*). More recent studies on gold ore tailings from Brazil, reported by *Oliveira et al. (2024)* and *Gomes et al. (2019)*, indicated hydraulic conductivity of 1.7×10^{-7} cm/s and 9.5×10^{-6} cm/s, respectively. The results obtained in this research are consistent with those reported in the literature and also reflect the typical behavior of decreasing hydraulic conductivity with decreasing void ratio as described by *Carneiro et al. (2023)*.

Carneiro et al. (2023) highlight the challenges in defining reference hydraulic conductivity values for tailings, as several factors influence their behavior. These factors directly affect hydraulic conductivity, which can vary by up to a factor of five times for the same tailings depending on the void ratio.

In accordance with current practice, permeability tests were carried out on previously saturated specimens to allow comparison with values reported in the literature. However, it is important to complement the studies by performing tests on unsaturated specimens, as filtered tailings stacks tend to remain in an unsaturated condition (*Cacciuttolo & Campomanes, 2022*).

3.2.3 Analysis of critical state condition

From the graphical analysis of the $\eta=q/p' \times \varepsilon_a$ curves, the 28 selected test specimens indicated that the critical state had been reached (Figure 7a and Figure 7b).

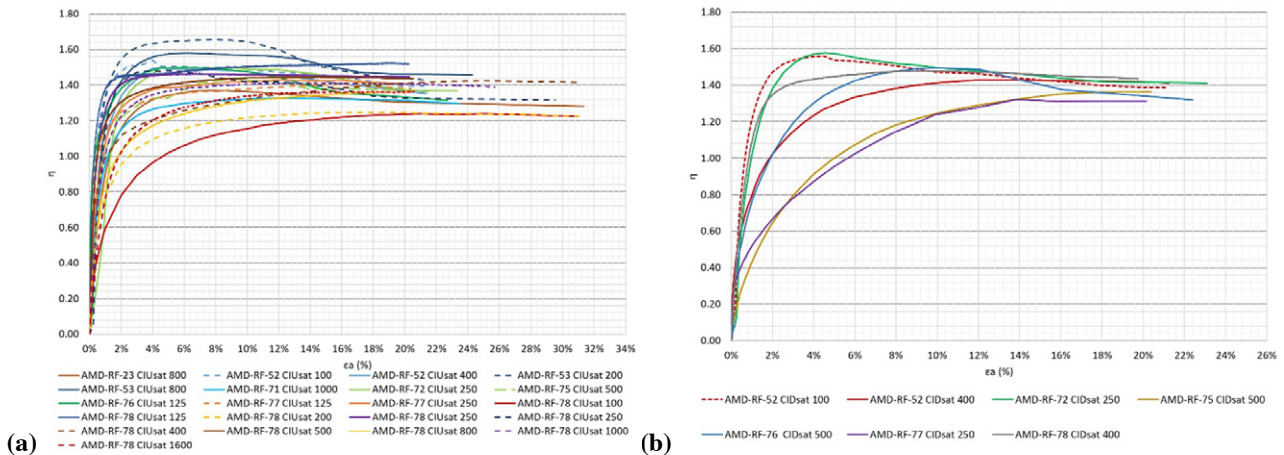


Figure 7. Plot of $\eta=q/p'$ versus ε_a . (a) CIU_{sat} tests, (b) CID_{sat} tests.

Considering the variability of the η versus ε_a curves, which may be attributed to the heterogeneity among the tested specimens, the specimens were grouped according to their grain size distribution to highlight possible changes in geomechanical behavior related to this characteristic. Four distinct groups were defined based on the similarity of their grain size distribution curves. The grain size distribution for each group, along with the corresponding average curves, is presented in Figure 8.

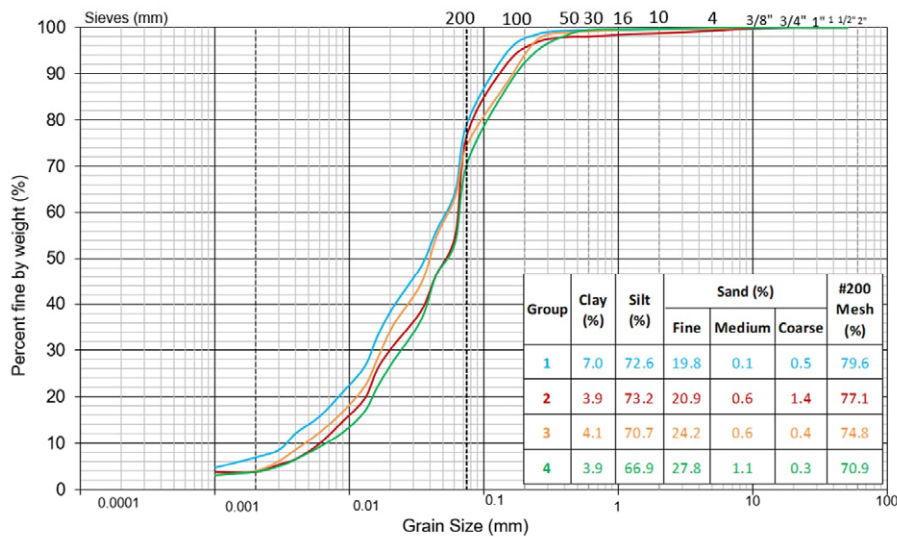


Figure 8. Average grain size distribution curves of the sample groups selected for critical state condition analysis.

For each set of tests within the same group, the Critical State Line (CSL) was plotted on the planes $e \times \ln p'$ (Figure 9a) and $p' \times q$ (Figure 9b) planes. To facilitate analysis, each CSL was drawn in the same color as the grain size distribution curve of the corresponding group. It is worth noting that the CSLs determined for the four groups differ in both position and slope, evidencing significant variation between the CSLs of tailings from the same stack and highlighting the influence of the grain

size composition on this variation. This analysis indicates that, although silt is the predominant particle size fraction of the tailings, the sand fraction may be a determining factor in the geomechanical behavior of the material.

Fourie & Papageorgiou (2001), in a study of four particle size distribution curves of gold ore tailings, addressed the difficulty of defining a unique CSL for certain tailings. In this study, four different CSLs were identified, with the material containing the highest fines content exhibiting a CSL located below the others. Xu and Coop (2017), Li et al. (2018), Li and Coop (2018), and Coop (2015) argue that the CSL uniqueness theory does not apply to tailings, as these materials exhibit transitional behavior, which may be related to their grain size distribution, post-compaction void ratio, and particle shape.

The findings of this study regarding the occurrence of different CSLs for the same tailings corroborate the behavior observed by the authors mentioned above. Figure 9a shows that CSL4 (in green), associated with the particle size distribution curve with the lowest fines content (Figure 8), is located above the other CSLs obtained — except for CSL1 (blue). CSL2 (in red) and CSL3 (in orange), which have higher fines content than CSL4, are positioned below all other CSLs obtained (Figure 9a), indicating the need for more compaction cycles to induce a dilatant response in the material. The CSL1 (blue) was an exception, being positioned higher despite its higher fines content, as also observed by Carrera et al. (2011), suggesting a possible change in behavior with increased silt content. Grain shape and mineralogy — not evaluated in this study — may also contribute to this distinct behavior.

The observed similarity between the slopes of CLS3 and CLS4 ($\lambda = 0.139$ and 0.162 , respectively), as well as the similarity between their corresponding average sand fractions, suggests that grain size distribution may influence both the M and λ values.

Despite the minor variations observed in the CSLs established in the $p' \times q$ plane, the variability of the CSLs in the $e \times \ln p'$ plane is significant and appears to be associated with the grain size variations identified. This observation is consistent with the findings of Velten et al. (2022) in studies on gold ore tailings.

The state parameters (ψ) of the test specimens presented in Figure 9 ranged from -0.3 to 0.12 , as follows: -0.07 to 0.06 (CSL1); -0.18 to 0.00 (CSL2); -0.17 to 0.12 (CSL3); and -0.3 to 0.02 (CSL4). Based on the stress path of the specimens, 23 of them exhibited dilatant behavior, while the remaining 7 exhibited contractile behavior.

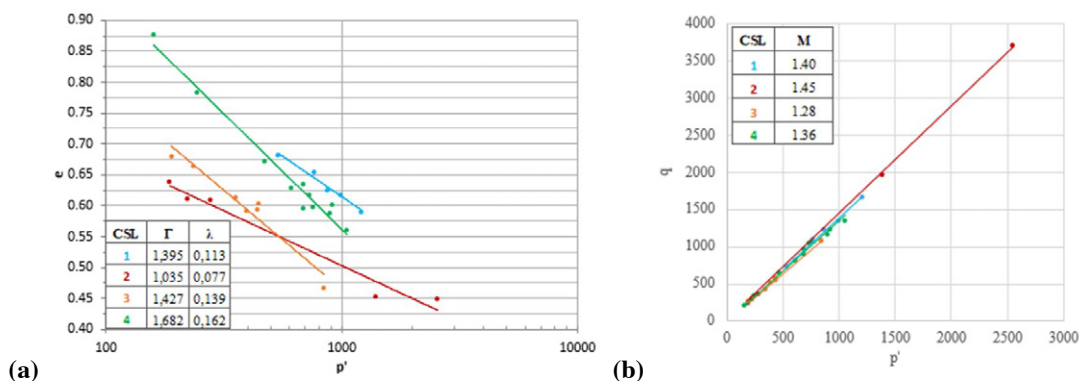


Figure 9. CSLs obtained: (a) represented in the $e \times \ln p'$ plane; (b) represented in the $p' \times q$ plane.

The critical state parameters obtained in this study are compared with those reported by other authors who analyzed gold ore tailings (see Table 3), where relatively similar results can be observed. However, the slopes of the critical state lines (λ) ranging from -0.077 to -0.162 , are higher than those reported in the literature (0.05 to 0.066). Regarding the intercept parameter Γ , the results of the present study (1.035 to 1.682) fall within the range proposed by the same authors (0.80 to 2.64). The slope of the critical state line in the p' - q plane (M), which ranges from 1.28 to 1.45 , is slightly higher than the results reported in other studies (1.13 to 1.39), reflecting a critical state friction angle of 31.9° to 35.7° , also higher than those observed in the referenced literature (28° to 33°). The findings of this study suggest that a minimum DC of 96% is required for the construction of the tailings stack using the material analyzed.

Table 3. Comparison of critical state parameters with values from other studies.

Author	λ	Γ	M	Φ'_{cs}
<i>Bedin (2010)</i>	0.045 – 0.058	2.34 – 2.64	1.33	33°
<i>Bonin et al (2022)</i>	0.066	0.80	1.20-1.39	-
<i>Oliveira et al. (2024)</i>	0.05	1.97	1.13	28°
Present study	0.077 – 0.162	1.035 – 1.682	1.28 – 1.45	31.9° – 35.7°

4. CONCLUSIONS

Laboratory and field tests were conducted to evaluate the compaction behavior, physical characterization, hydraulic conductivity, and shear strength parameters of the tailings. In addition to expanding the geotechnical database specific to filtered gold tailings, the results emphasize the significance of compaction methods in achieving desirable mechanical behavior and highlight the influence of material heterogeneity in defining geotechnical parameters.

Field test results, supported by findings in the literature, indicate that the layer thickness for these stacked tailings should be limited to 30 cm. Compaction using a smooth drum roller proved more effective in producing a homogeneous and well-compacted material. In contrast, compaction using track equipment—whether for 30 cm or 50 cm thick layers—resulted in greater variability and notable differences between the degrees of compaction at the top and bottom of the layers, indicating inefficient compaction. Achieving adequate compaction levels (DC > 96%) required a minimum of five to six compaction cycles.

Laboratory tests showed that the grain size distribution, compaction behavior, and hydraulic conductivity of the studied tailings fall within the range reported for other gold ore tailings in the literature. The critical state analysis based on the Critical State Soil Mechanics (CSSM) framework revealed significant variation in the Critical State Lines (CSLs), associated with the material's grain size composition. Except for one group, higher fines content generally corresponded to lower CSL positions, indicating a greater need for compaction to achieve dilative behavior. This variability reinforces the need for continuous (QA/QC) monitoring throughout the service life of the stacks, and for adapting compaction criteria in response to material changes and site-specific constraints, ensuring the long-term structural stability of the stacks.

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CRedit authorship contribution statement

Mayara Ferreira Rodrigues: Conceptualisation, Formal analysis, Writing - original draft. **Márcio de Souza Soares de Almeida:** Formal analysis, Supervision, Validation, Writing – review & editing. **Marcos Barreto de Mendonça:** Formal analysis, Supervision, Validation, Writing – review & editing. **Jaime Pinheiro:** Writing – review & editing.

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