The paper was published in the Proceedings of the 8th International Symposium on Deformation Characteristics of Geomaterials (IS-PORTO 2023) and was edited by António Viana da Fonseca and Cristiana Ferreira. The symposium was held from the 3rd to the 6th of September 2023 in Porto, Portugal.

Proceedings of the 8th International Symposium on
DEFORMATION CHARACTERISTICS OF GEOMATERIALS
Porto, 3rd - 6th September 2023

On the behavior of compacted filtered iron ore tailings submitted to high pressures

João Paulo Silva[1], *João Vítor* Carvalho[2], *Alexia Cindy* Wagner[2], and *Nilo Cesar* Consoli[2#]

[1]*VALE S.A, Exploration and Mineral Projects – Mineral Development Centre, Santa Luzia, MG, 33040-900, Brazil*
[2]*Universidade Federal do Rio Grande do Sul, Graduate Program in Civil Engineering, Porto Alegre, RS, 90035-190, Brazil*
[#]*Corresponding author: consoli@ufrgs.br*

ABSTRACT

Mine tailings have been disposed of in a slurry form in tailings dams for many years. However, recent disasters involving conventional disposal in dams reinforced the need for alternative structures to store these materials safely. One alternative is dry stacking of tailings. In these structures, tailings are filtered to low moisture content and then compacted in layers. Due to material compaction, dry stacks tend to be stable and are usually built with elevated heights to use the available area better. So, it becomes essential to understand the mechanical behavior of tailings subjected to high pressures, especially concerning the possibility of grain breakage. In this context, the present research focuses on studying the geotechnical behavior of iron ore tailings from different stages of ore beneficiation plants in Quadrilátero Ferrífero, Brazil, when subjected to high pressures both in compression and in shear paths. The results demonstrate that the inclusion of fines can change the geotechnical performance of the dry stack tailings considering the same compaction energy (greater strength, stiffness, and lower permeability) both in drained and undrained conditions. No breakage could be identified for the stress level studied (6 MPa).

Keywords: tailings; dry stacking; high pressures; particle breakage.

1. Introduction

Recent disasters involving tailings' dams have highlighted the need for new disposal schemes as alternatives to conventional methods. One possibility for the disposal of tailings is dry stacking (Consoli et al. 2022; Gomes, De Tomi, and Assis 2016). This method consists of filtering the tailings to lower moisture contents and disposing of this material in a compacted form to produce a stable stack (Lupo and Hall 2011; Davies 2011). This type of Tailings' Storage Facilities (TSF) now presents a viable alternative for the safe disposal of tailings as the risks of liquefaction are diminished, besides other advantages such as the better use of the landform and water management (Edraki et al. 2014; Spitz and Trudinger 2019).

The dry stacking method can produce high-rise structures with hundreds of meters, thus inducing high pressures at the base. This paper investigates the behavior of two compacted filtered iron ore tailings with distinct grading. For this, drained and undrained triaxial compression tests were performed up to high pressures to evaluate the strength and stiffness response of the two tailings. After each triaxial test, the resulting particle size distribution of the samples was assessed to evaluate the influence of particle breakage on the computed behavior and the differences arising from the different initial gradings. Furthermore, oedometer tests were conducted for both tailings to obtain a complete material response.

2. Materials and methods

This section describes the materials considered and the test methods used for this research.

2.1. Materials

The iron ore tailings (IOT) studied are from Quadrilátero Ferrífero (QF) located in the province of Minas Gerais, Brazil. Iron ore beneficiation involves activities from crushing and screening to more sophisticated processes to upgrade the ore quality. The two iron ore tailings studied present different gradings due to different beneficiation stages. The IOT_A was obtained prior to the flotation process, while the IOT_B was recovered after the flotation process. Due to this, the tailings have different iron contents, which impacts their properties.

Fig. 1 presents the particle-size distribution (PSD) curves obtained via laser diffraction analysis. Both tailings are classified as silty sand (SM) following the Unified Soil Classification System (ASTM 2017a). The specific gravity (IOT_A = 3.05 and IOT_B = 2.97) was evaluated according to ASTM D854 (ASTM 2014). The compaction characteristics were assessed using the standard effort in agreement with ASTM D698 (ASTM

2021), and these results are shown in Fig. 2. The Atterberg limits were evaluated according to ASTM D4318 (ASTM 2017b) and both tailings are non-plastic.

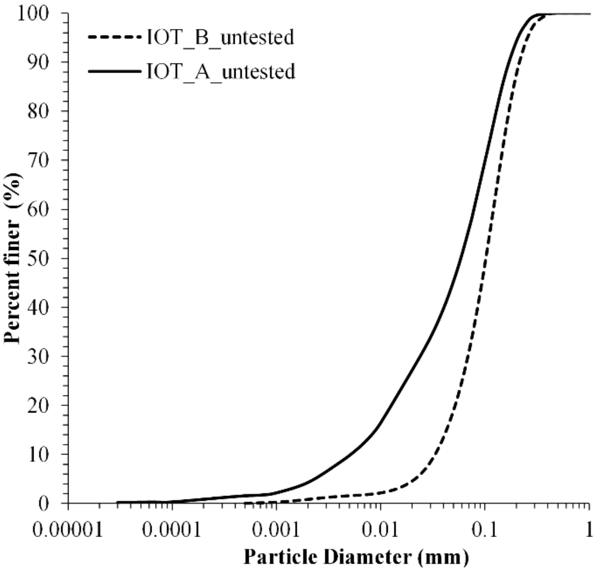


Figure 1. Particle size distribution of the two tailings before testing.

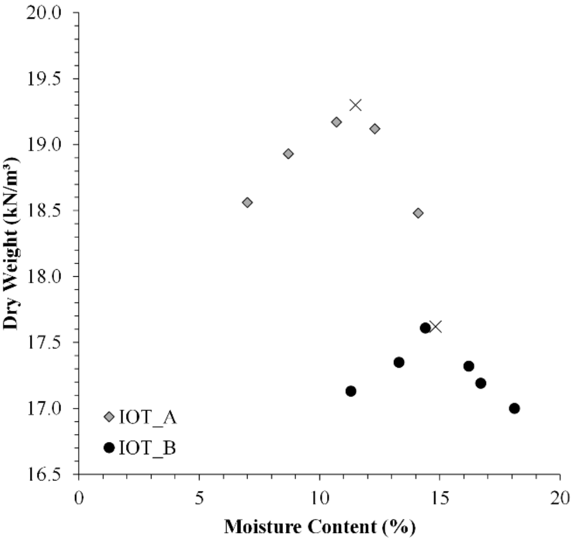


Figure 2. Compaction curves for tailings A and B.

Fig. 3 exhibits the hydraulic conductivity calculated for different loading stages during the oedometer tests. The samples used were molded at the compaction degree of 100%, considering the standard effort. Hydraulic conductivity is a property of great importance in dry stack design, as it directly influences the stability of the stacking. The infiltration of water in the structure can cause a reduction of the overall safety factor both by promoting an undrained shear path and by causing the erosion of the stacking surface (Furnell et al. 2022). The values measured are very low, which ensures low infiltration in the structure. As IOT_A has a higher dry weight due to the higher fines content, its permeability is lower than IOT_B. Also, the permeability of the structure tends to decrease with increasing pressures (due to the dry stack rising). The characterization of tailings in terms of permeability is crucial as the definition of parameters for the adequate modeling and designing of the structure at the different conditions it will be subjected during its lifetime (Viana da Fonseca et al. 2022).

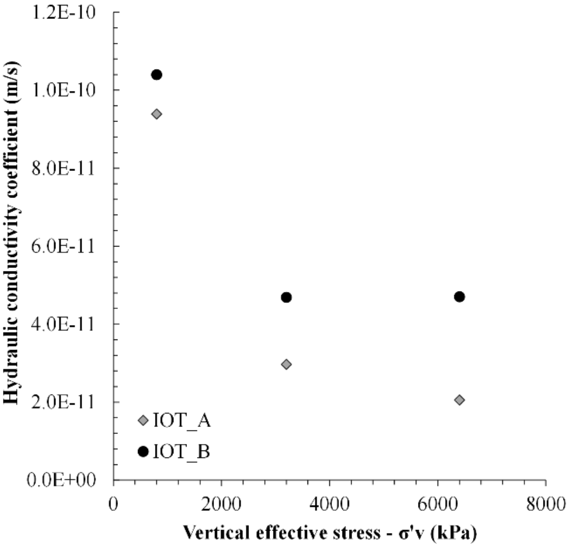


Figure 3. Hydraulic conductivity at different pressures for tailings A and tailings B.

2.2. Methods

Oedometer tests assessed the one-dimensional compression behavior up to vertical stresses of 6 MPa. Three drained triaxial compression tests and one undrained triaxial compression test were conducted for each tailing up to 6 MPa to evaluate the stress-strain response of the different tailings. Also, the stiffness of the materials was assessed by bender elements.

2.2.1. Oedometer tests

Two oedometer tests were conducted on the tailings in oedometers with diameters of 38 mm and a maximum applied load of approximately 6 MPa. The samples were prepared using the moist tamping technique (Ladd 1978; Suits et al. 2003) for a 100% standard Proctor compaction degree. All tests followed the recommendations of ASTM D2435 (ASTM 2011).

2.2.2. Triaxial tests

Cylindrical specimens of 50 mm in diameter and 100 mm in height were molded through moist tamping. For this, wet tailings layers were deposited inside a split mold and manually tamped to the assigned degree of compaction. The degree of compaction relative to 100% of the standard effort was chosen to reproduce the usual compaction level used for the iron ore tailings dry stacking in the field. Conventional Isotropically Consolidated Drained (CID) and Isotropically

Consolidated Undrained (CIU) triaxial tests were undertaken to assess the mechanical response of the iron ore tailings at a broad range of initial effective confining pressures (100 kPa to 6,000 kPa). The recommendations stated by ASTM D7181 (ASTM 2020a) and ASTM D4767 (ASTM 2020b) were followed. Thus, all tests were conducted on fully saturated specimens with B-values greater than 0.95.

2.2.3. Bender elements

Two samples (one for each tailing) in 100% compaction degree condition were isotropically consolidated incrementally in the following stages approximately: 50 kPa, 150 kPa, 300 kPa, 600 kPa, and 1,200 kPa. In each stage, bender elements (BE) tests were conducted. Then, the specimens were unloaded, and the BE tests were repeated in each unloading stage.

3. Results and Discussion

3.1. One dimensional compression behavior

Fig. 4 shows the compression data for the two tailings. A comparison of the materials shows that the IOT_A has a flatter compression path, indicating that the finer material is slightly more compressible. As other authors (Carrera, Coop, and Lancellotta 2011) observed, 1D-NCL moves downwards as the fines content increases. This behavior feature is related to the presence of fines in the granular matrix, providing better packing and higher dry densities compared to coarser materials. Both curves are fairly flat up to the pressures tested with no clear yield point. Coop (1990), when studying the behavior of carbonate sands, suggested that the marked yield point in compression of granular materials would be related to the change of the primary volumetric deformation mechanism from particle rearrangement and distortion to particle breakage. Thus, the inexistence of this yield point up to the stresses evaluated indicates that even though breakage may have occurred, it still is not the primary deformation mechanism and may be restricted to the breakage of small angularities of the particles.

The unloading curves at different loading stages are almost linear and with low slopes. This behavior suggests that the elastic deformation component is negligible, as a minimal amount of deformation is recovered. The finer tailings presented a slightly higher slope on unloading, as they achieved denser states than the coarser material, implying that additional axial strains are required to reach higher densities at higher stress levels (Yamamuro, Bopp, and Lade 1996).

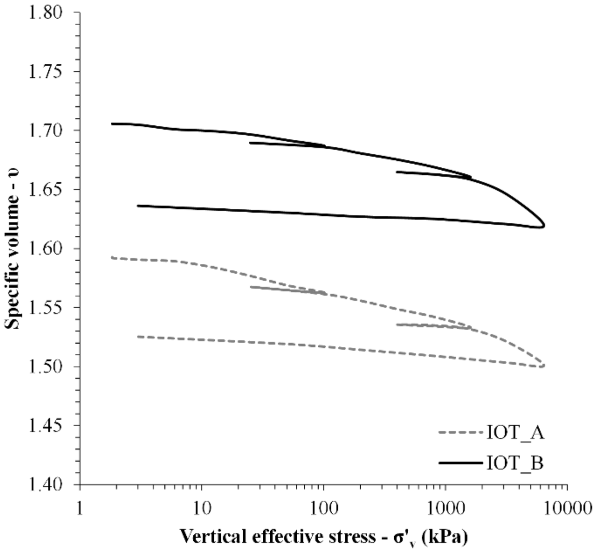


Figure 4. Oedometer results for tailings A and tailings B.

3.2. Drained triaxial response

Fig. 5 presents the mechanical response of the tailings under CID (Consolidated Isotropically Drained) shearing tests. It is possible to observe important differences between the two types of tailings. Although they are prepared to the same degree of compaction, the IOT_B specimens show a more ductile response accompanied by a more contractive behavior for all stresses levels evaluated. Then, the IOT_A specimens have a clear peak strength associated with a more pronounced dilatant behavior that is associated with a great fines content and the lower initial void ratio at molding.

In practice, the controllable factor usually is the compaction energy applied to the tailings. This means that by applying the same degree of compaction to the stacks the behavior achieved by tailings with different fines content would differ greatly. This condition is clearly shown in Fig. 5. The response of the materials is directly linked to their gradations. The presence of fines, which provided a better packing and denser states, induces more contacts between the particles. This higher number of contacts provide the slightly greater mobilized strengths.

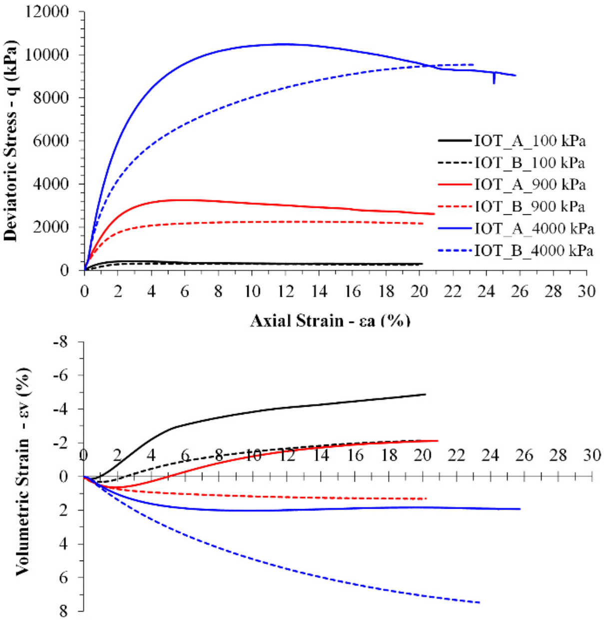
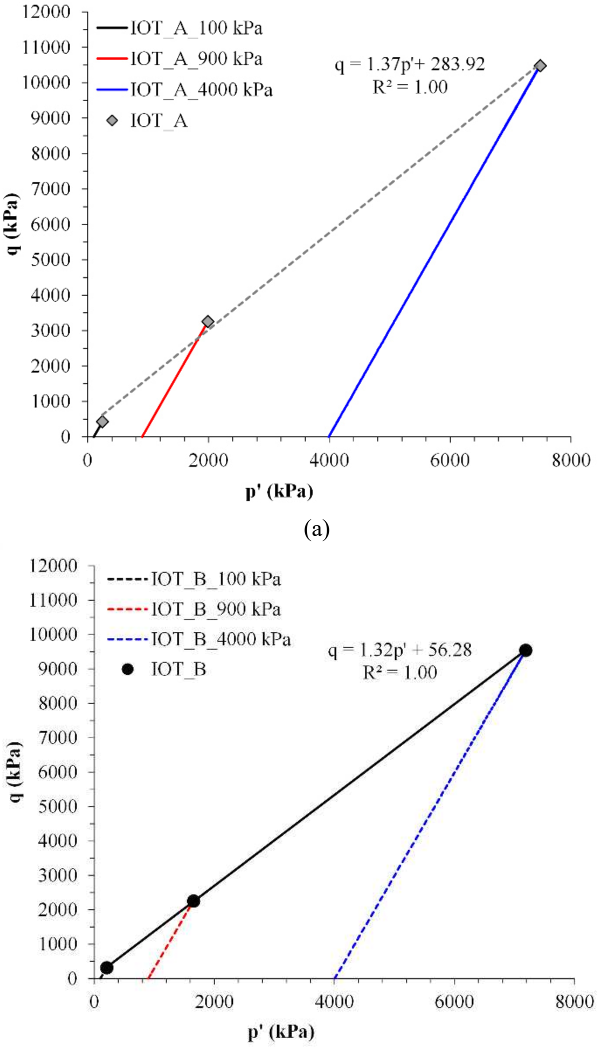


Figure 5. Comparison of stress-strain results for drained standard triaxial compression paths of tailings A and B.

Fig. 6 plots the stress paths and the peak strength envelopes for both tailings. The two iron ore tailings presented similar peak friction angles (33.89° for IOT_A and 32.75° for IOT_B), with IOT_A presenting slightly higher values. For the cohesive intercept determined, the IOT_A presented much higher values than IOT_B, 283.92 kPa, and 56.26 kPa, respectively. The strength of soils is a sum of contributions, one from the friction between the soil particles and another from the energy dissipated for the rearrangement of the grains, called interlocking (Taylor 1948; Jefferies 2021). The finer particles provided a better packing, resulting in a higher dilation rate for IOT_A tests. This arrangement also mobilizes higher strengths as the rearranging of the grains requires more energy. These higher strengths mobilized originate the differences noticed on peak friction angles, and cohesive intercepts for the tailings studied.

3.3. Undrained triaxial response

Fig. 7 presents the response of the iron ore tailings isotropically consolidated and sheared under undrained conditions (CIU tests). The samples showed a more compressive volumetric behavior trend with a positive change of pore-pressure generation during shearing due to high confining stress, despite their initial dense state. Positive pore pressure increments registered during shearing induced a more significant loss of strength with a strain-softening behavior for IOT_B. It can be noticed that the greater fines content results in a more stable condition for the material when subjected to undrained loading at high stresses.



(a)

(b)

Figure 6. Strength envelopes and stress paths of drained triaxial tests for (a) tailings A and (b) tailings B.

Fig. 8 shows examples of stress paths for both undrained tests. It is observed that IOT_B test presents a "C" shaped stress path, but the strain softening does not lead to the occurrence of true liquefaction. For IOT_A the stress path is "S" shaped, and a phase transformation point is well defined. This test has contractive behavior until a minimum mean effective stress or phase transformation is reached, with the pore water pressures increasing quickly, and then the behavior changes to dilative. Thus, the tailings with higher content of fines present a safer condition for stacking considering the possible occurrence of undrained behavior.

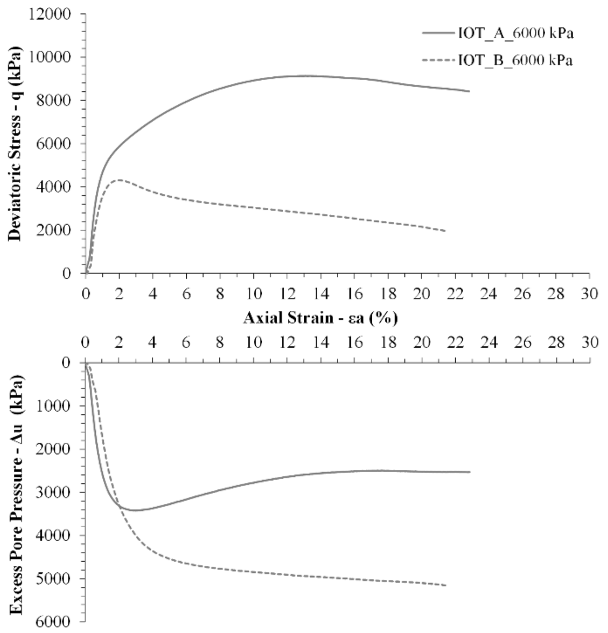


Figure 7. Comparison of undrained triaxial compression for tailings A and tailings B.

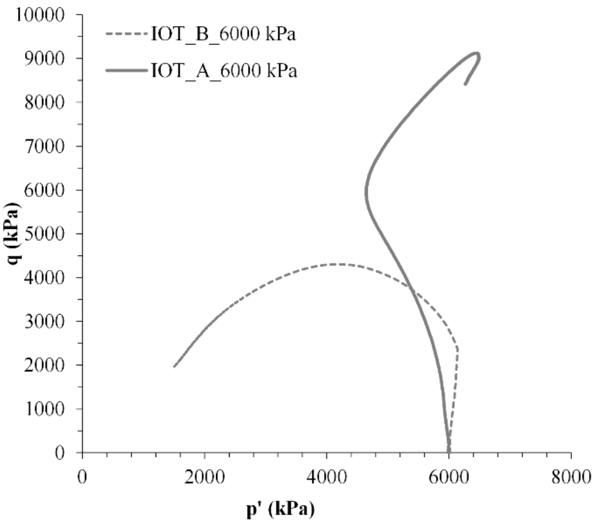


Figure 8. Undrained stress paths of tailings A and tailings B.

3.4. Overall triaxial response

The stress-strain responses of the iron ore tailings under drained and undrained conditions are presented in Fig. 9. The deviatoric stress (*q*) was normalized by the initial mean effective stress (p'_0). Thus, it is possible to compare the normalized behavior considering the broad range of utilized confining pressures. The lowest confining pressure tests (100kPa) show stress-strain curves that rise quickly to the peak stress with the largest normalized deviatoric stress value and the smallest axial strain at the peak among all the tests. With the increase in confining pressure, the initial stiffness of the curves tends to decrease (the peak occurs at higher axial strain, and the maximum normalized deviatoric stress decreases). The stress-strain curves flattening was also observed in higher-pressure tests by (Yamamuro and Lade 1996) for dense sand.

Undrained tests reach lower peak strengths despite the initial stiffness being similar to drained tests with similar confining pressure. Again, the finer tailings (IOT_A) achieve higher strengths for the same initial confinement pressure (p'_0) than the respective test in the IOT_B.

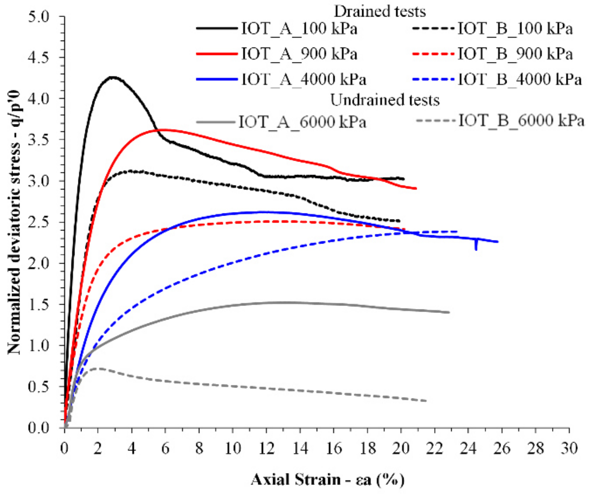


Figure 9. Normalized stress-strain results for tailings A and tailings B.

3.5. Maximum Shear Modulus

Fig. 10 shows the elastic shear modulus (G_{max}) determined with BE testing to both tailings in the dense state (100% standard Proctor). It is observed that the stiffness increases with the confining pressure applied. Power law fits both results well with a similar exponent. The difference in stiffness could be adjusted by adopting a scalar value because the IOT_A was stiffer due to the higher fines content and better packing of the specimens.

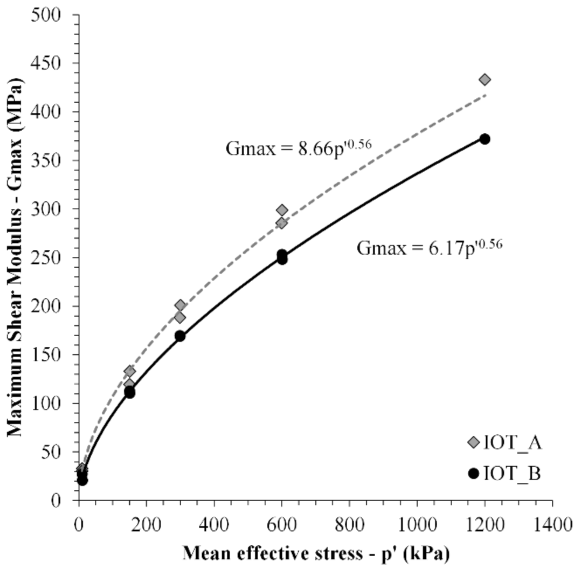


Figure 10. Maximum shear modulus from bender elements on tailings A and tailings B.

3.6. Particle breakage

After the triaxial tests, the samples were retrieved for grain size distribution analysis. Fig. 11 shows the obtained grading for all specimens. No particle breakage was verified for the different pressures applied in drained and undrained conditions. Despite some differences in the curves, the amount of breakage determined is smaller than the natural variability of gradations produced in beneficiation plants of the iron ore tailings (Crystal and Hore 2018). These results agree with the verified behavior in both compression and shearing. The higher confining pressures assessed in this work were insufficient for the grain breakage to occur and be noticed by particle size distribution analysis. It is expected that the stress states experienced by the specimens have induced some degree of particle breakage. However, it could be limited to the breakage of small angularities and reduction of surface roughness of the particles.

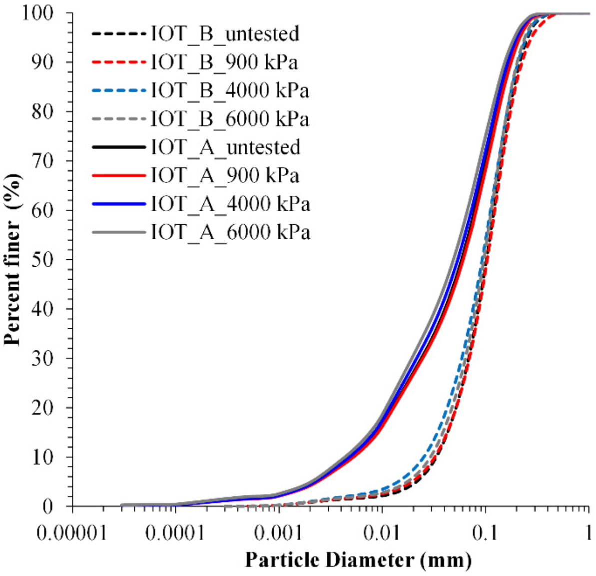


Figure 11. Particle size distributions after testing at different confining pressures.

4. Conclusions

The paper presents the drained and undrained mechanical response of two tailings with different gradings. The following conclusions can be drawn, considering the study conducted.

Fines in the granular matrix caused the two tailings compacted to the same compaction energy to behave differently. The finer material presented higher strength, lower compressibility, and lower hydraulic conductivity. These results are associated with better packing provided by the presence of fines. The smaller particles fill the voids between coarser particles promoting a higher number of contacts between the grains and the change in behavior observed. In particle size distribution analysis, no particle breakage was noticed for the pressures assessed for either of the tailings.

Thus, considering the application for dry stacking, the finer tailings have presented a more interesting behavior. Despite the challenges of filtering finer tailings, their inclusion can be beneficial. The lower hydraulic conductivity reduces the water infiltration in the structure, favoring its security and serviceability. The higher strength mobilization allows for considering steeper slopes and higher heights, which allow better use of the available landform.

Acknowledgments

The authors wish to express their appreciation to VALE S.A., MEC/CAPES (PROEX), and Brazilian Research Council (CNPq) for their support of the research group.

References

ASTM. 2011. “Standard Test Methods for One-Dimensional Consolidation Properties of Soils Using Incremental Loading.” 2435. ASTM 2435. West Conshohocken, PA: ASTM D2435.

———. 2014. “Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer.” 584. ASTM D854. West Conshohocken, PA: ASTM D854.

———. 2017a. “Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System).” D2487. ASTM D2487. West Conshohocken, PA: ASTM D2487.

———. 2017b. “Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils.” D4318. ASTM D854. West Conshohocken, PA: ASTM D4318.

———. 2020a. “Standard Test Method for Consolidated Drained Triaxial Compression Test for Soils.” Norma técnica 7181. ASTM D7181. West Conshohocken, PA: ASTM D7181.

———. 2020b. “Standard Tests Method for Consolidated Undrained Triaxial Compressio Test for Cohesive Soils.” Norma técnica 4767. ASTM D4767. West Conshohocken, PA: ASTM D4767.

———. 2021. “Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort (12,400 Ft-Lbf/Ft^3 (600 KN-m/M^3)).” D698. ASTM D854. West Conshohocken, PA: ASTM D698.

Carrera, A., M. Coop, and R. Lancellotta. 2011. “Influence of Grading on the Mechanical Behaviour of Stava Tailings.” *Géotechnique* 61 (11): 935–46. https://doi.org/10.1680/geot.9.P.009.

Consoli, Nilo Cesar, Jordanna Chamon Vogt, João Paulo Sousa Silva, Helder Mansur Chaves, Hugo Carlos Scheuermann Filho, Eclesielter Batista Moreira, and Andres Lotero. 2022. “Behaviour of Compacted Filtered Iron Ore Tailings–Portland Cement Blends: New Brazilian Trend for Tailings Disposal by Stacking.” *Applied Sciences* 12 (2): 836. https://doi.org/10.3390/app12020836.

Coop, M. R. 1990. “The Mechanics of Uncemented Carbonate Sands.” *Géotechnique* 40 (4): 607–26. https://doi.org/10.1680/geot.1990.40.4.607.

Crystal, C, and C Hore. 2018. “Filter-Pressed Dry Stacking: Design Considerations Based on Practical Experience.” In *Tailings and Mine Waste Conference*. Keystone, Colorado, USA.

Davies, Michael. 2011. “Filtered Dry Stacked Tailings : The Fundamentals.” In *Tailings and Mine Waste Conference*. Vancouver, Canada: The University of British Columbia. https://doi.org/10.14288/1.0107683.

Edraki, Mansour, Thomas Baumgartl, Emmanuel Manlapig, Dee Bradshaw, Daniel M. Franks, and Chris J. Moran. 2014. “Designing Mine Tailings for Better Environmental, Social and Economic Outcomes: A Review of Alternative Approaches.” *Journal of Cleaner Production* 84 (December): 411–20. https://doi.org/10.1016/j.jclepro.2014.04.079.

Furnell, Erin, Ksenia Bilaniuk, Matthew Goldbaum, Mohammed Shoaib, Omar Wani, Xinyi Tian, Zhirong

Chen, Darryel Boucher, and Erin Rae Bobicki. 2022. "Dewatered and Stacked Mine Tailings: A Review." *ACS ES&T Engineering* 2 (5): 728–45. https://doi.org/10.1021/acsestengg.1c00480.

Gomes, Reinaldo Brandao, Giorgio De Tomi, and Paulo Santos Assis. 2016. "Iron Ore Tailings Dry Stacking in Pau Branco Mine, Brazil." *Journal of Materials Research and Technology* 5 (4): 339–44. https://doi.org/10.1016/j.jmrt.2016.03.008.

Jefferies, Michael. 2021. "On the Fundamental Nature of the State Parameter." *Géotechnique*, November, 1–10. https://doi.org/10.1680/jgeot.20.P.228.

Ladd, Rs. 1978. "Preparing Test Specimens Using Undercompaction." *Geotechnical Testing Journal* 1 (1): 16. https://doi.org/10.1520/GTJ10364J.

Lupo, J., and J. Hall. 2011. "Dry Stack Tailings - Design Considerations." In *Tailings and Mine Waste '10: Proceedings of the 14th International Conference on Tailings and Mine Waste, Vail, Colorado, USA, 17 - 20 October 2010*. Boca Raton, Fla.: CRC Press.

Spitz, KARLHEINZ. TRUDINGER, and John Trudinger. 2019. *MINING AND THE ENVIRONMENT: From Ore to Metal, 2 Edition.* Place of publication not identified: CRC Press.

Suits, L D, Tc Sheahan, Jd Frost, and J-Y Park. 2003. "A Critical Assessment of the Moist Tamping Technique." *Geotechnical Testing Journal* 26 (1): 9850. https://doi.org/10.1520/GTJ11108J.

Taylor, Donald W. 1948. *Fundamentals of Soil Mechanics*. New York, USA: John Wiley & Sons.

Viana da Fonseca, António, Diana Cordeiro, Fausto Molina-Gómez, Davide Besenzon, António Fonseca, and Cristiana Ferreira. 2022. "The Mechanics of Iron Tailings from Laboratory Tests on Reconstituted Samples Collected in Post-Mortem Dam I in Brumadinho." *Soils and Rocks* 45 (2): 1–20. https://doi.org/10.28927/SR.2022.001122.

Yamamuro, Jerry A., Paul A. Bopp, and Poul V. Lade. 1996. "One-Dimensional Compression of Sands at High Pressures." *Journal of Geotechnical Engineering* 122 (2): 147–54. https://doi.org/10.1061/(ASCE)0733-9410(1996)122:2(147).

Yamamuro, Jerry A., and Poul V. Lade. 1996. "Drained Sand Behavior in Axisymmetric Tests at High Pressures." *Journal of Geotechnical Engineering* 122 (2): 109–19. https://doi.org/10.1061/(ASCE)0733-9410(1996)122:2(109).