Shear response of iron ore tailings under monotonic loadings

Guilherme Schmitt Medina[1], *Helena Portela* Farenzena[1], *Bráulio Araújo* Rodrigues[2], *João Paulo* Silva[2], *Lucas* Festugato[1], and *Nilo Cesar* Consoli [1,#]

[1]*Graduate Program in Civil Engineering, Universidade Federal do Rio Grande do Sul, Porto Alegre 90035-190, Brazil;*

[2]*Exploration and Mineral Projects—Mineral Development Centre, VALE S.A., Santa Luzia 33040-900, Brazil;*

[#]*Corresponding author: consoli@ufrgs.br*

ABSTRACT

Dry stacking is a disposition method that is quickly becoming a trend for the mining industry in Brazil. With several cases in which compacted mine tailings are positioned on the top of hydraulically disposed tailings which were placed into pits. The present research assessed the mechanical response of hydraulically disposed iron ore tailings collected from a pit that was formerly a mining site. To better understand the mechanical behaviour of mine tailings under such conditions, the investigation of their monotonic response is of great importance. The studied material was classified as a silty sand with traces of clay size. A very loose condition with distinct confining stresses was tested monotonically on a simple shear equipment. Simple shear tests were performed in an apparatus that can directly measure pore pressure, guaranteeing an effective stresses analysis. A plane strain condition was applied on fully saturated samples under undrained loading conditions. Results showed the agreement of the strength envelopes of monotonic stress paths, the effective friction angle of the material was 33.2º and no cohesive intercept.

Keywords: Mine tailings, simple shear, strength envelopes, effective stresses.

1. Introduction

Tailings are essentially composed of crushed rock waste particles (Wijewickreme et al. 2005). The characteristics of such material are highly variable, depending on ore composition and extraction processes (Li and Coop, 2019). A great proportion of mining tailings is generated during the mining processes of ores; for example, according to the FEAM (Minas Gerais State Environmental Agency), in 2017, 562 million tons of mining tailings were produced, only in the state of Minas Gerais, Brazil. Given the high generated volumes, different disposal methodologies have been implemented. The most commonly used discarding method is to dispose the tailings with slurry consistency (i.e., low solids and high moisture content), hydraulically depositing and storing in containment dams (Bastos et al, 2016). As a result of the conditions associated with the processing, transportation and deposition, tailings are commonly found saturated with a high void ratio (Festugato et al. 2015).

The appalling accidents occurred in upstream dams, in the past decades, forced a change in the way project and research is conducted all over the world. In recent years, new legislation regarding the construction and management of dams are being formulated (Schaper et al. 2020). For this reason, since 2019, building upstream tailings dams has been prohibited in Brazil, forcing the industry to search for news methods and feasible solutions.

According to Velten et al. (2022), the hydraulic disposition of tailings has become a major problem due to the uncertainty of its properties in situ. The disposal of agglomerated and stacked dry filtered tailings is a recent methodology that reduces dependency of using upstream dams. This technique has become viable with recent advances in large-scale material dewatering technologies (Davies 2011; Jewell et al. 2015; Li et al. 2016; Carneiro et al. 2020). In addition, there are cases in which compacted mine tailings stacking could be positioned above hydraulic fills, which were previously placed into closed pits or dams. There are unknown risks regarding the disposition of such new materials over the loose tailings. Consequently, further studies are required.

Velten et al. (2022) carried out an analysis of copper ore tailings in different locations of a same dam, focusing on triaxial tests to characterize dense samples, varying the compaction rate. Major studies were carried out by Consoli et al. (2022), which investigated the implications of adding cement to iron ore tailings, as an effective procedure to prevent liquefaction of such materials. Existing research in the field of ore tailings has mostly focused on filtered compacted (dense) samples, creating a gap in knowledge when it comes to hydraulically disposed materials. Therefore, the present study aims to evaluate a series of undrained monotonic simple shear tests, to investigate the static mechanical properties of loose samples of iron ore tailings. The main objective of this study was to obtain the basic geotechnical properties of the iron tailings and to disclosure their strength response, which are essential for the understanding of the mechanical behavior of this hydraulically disposed material.

2. Materials and Method

2.1. Mine tailings

Iron ore tailings (IOTs) were obtained from the Quadrilátero Ferrífero located in the province of Minas Gerais, Brazil. Material characterization (Tables 1 and Fig. 1) was performed by determining their solids unit weight (D854 (ASTM 2014)), Atterberg limits (D4318 (ASTM 2017b)) and grain size distribution (D7928 (ASTM 2017c)). IOTs was classified as silt with low plasticity, according to USCS classification (ASTM 2017a, b, c).

Table 1. Material physical properties

Properties	IOT
Liquid limit (%)	-
Plastic limit (%)	-
Plastic index (%)	Non- plastic
Solids unit weight (kN/m^3)	33.0
Medium sand (0.2 mm<diameter< 0.6 mm) (%)	0.32
Fine sand (0.06 mm< diameter <0.2 mm) (%)	17.6
Silt (0.002 mm<diameter< 0.06mm) (%)	72.9
Clay (diameter < 0.002 mm) (%)	9.3
USCS classification (ASTM 2017a, b, c)	ML

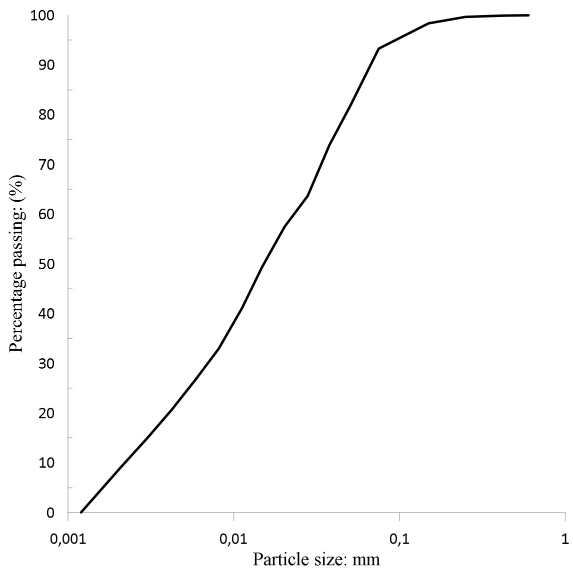

Figure 1. Particle size distribution of the studied mine tailings

2.2. Simple Shear test

Simple shear tests were executed in an apparatus developed by Corte et al. (2017), based in the Berkeley (Villet et al., 1985, Boulanger et al., 1993) and UWA (Mao and Fahey, 2003) devices. In this apparatus, the specimen is enclosed in an unreinforced latex membrane inside a pressurized cell. Fig. 2 schematically depicts the used testing apparatus. To impose plane-strain conditions, during shearing, the sample height is fixed,

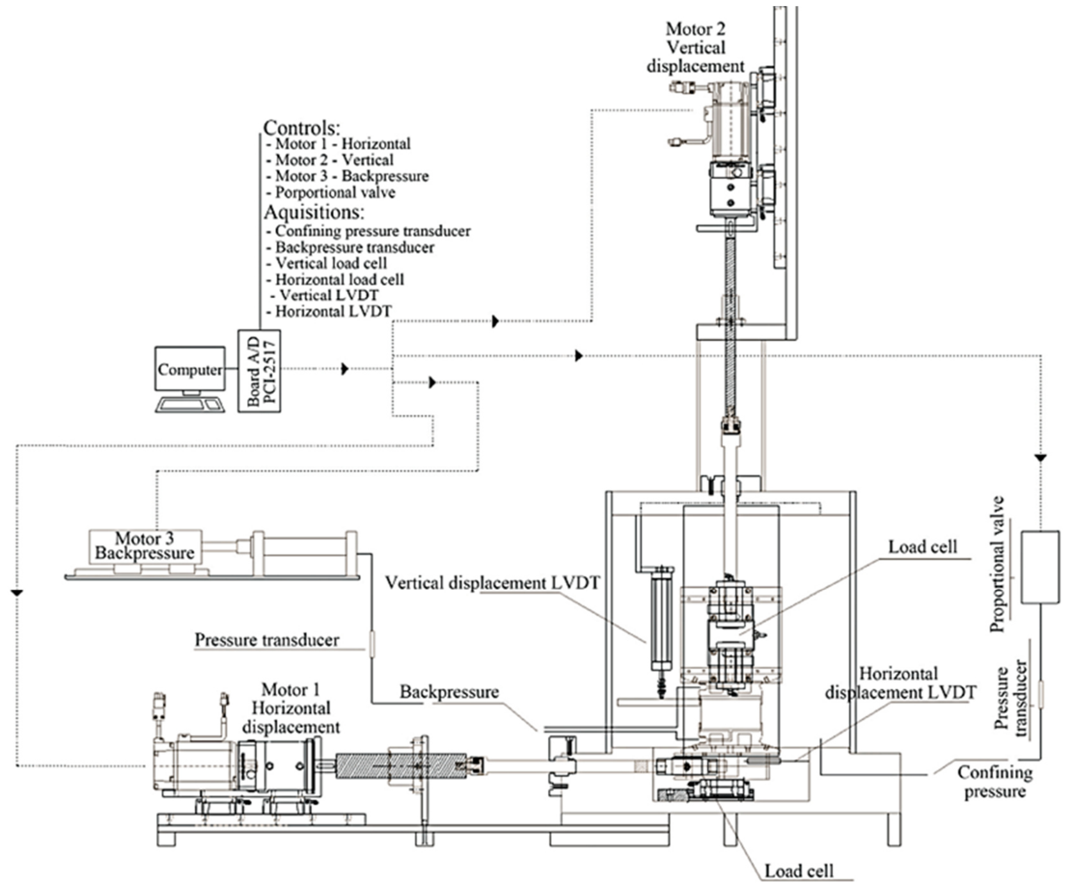

Figure 2. Simple Shear apparatus

which, coupled with the constant-volume undrained conditions imposed by the pore fluid, prevents any change in cross-sectional area. As the specimen is under constant-volume and plane-strain conditions, it becomes possible to rotate the principal stress – often representative of stress states in typical field situations (Budhu, 1988; Wood et al., 1979). In the equipment used in this study, it is possible to directly measure, with pressure transducers, confining and pore pressures during the whole test, which allows results to be truly evaluated in effective stresses. As explained by Corte et al. (2017), the shear stress τ refers to the shearing loads in the horizontal direction (F_h/diameter of the sample), while the strain caused by shearing, γ, is the ratio between the horizontal displacement and height of the specimen. The principal effective stresses (σ'_1, σ'_2, σ'_3) can be obtained from the equation:

$$\sigma'_{1,3} = \frac{\sigma'_v+\sigma'_h}{2} \pm \sqrt{(\frac{\sigma'_v-\sigma'_h}{2})^2 + \tau^2} \quad (1)$$
$$\sigma'_2 = \sigma'_h$$

Fig. 3 shows an image of the equipment used for the simple shear tests.

Figure 3. Used simple shear equipment.

2.3. Sample preparation and test procedure

For simple shear tests, specimens of 100 mm diameter and 50 mm height were tested. The maximum void ratio was measured utilizing ASTM D 4254 (2017d), method B, which showed good response in determining the maximum void ratio of silty sands according to Salgado et al. (2000). In this research, the maximum void ratio found was 1.3, so the dry unit weight of 14.3 kN/m³ was utilized. All specimens were moulded with a moisture content of 10%, following the undercompaction method proposed by Ladd (1978). Due to the fact that the present study used one layer, no adjustment of mass per layer was used. Specimens considered suitable for testing met the following criteria: degree of compaction between 99% and 101%; water content within 0.5% of the target value; diameter within 0.5 mm of the target value; and height within 1 mm of the target value.

The stages of the simple shear test are similar to those of a triaxial test. To allow application of back pressure in the specimen, a latex membrane (0.5 mm) was used. Furthermore, increments of confining pressure and back pressure were applied to the sample up to a satisfactory *B* parameter (at least 0.97 after Skempton (1954)). The monotonic tests were executed on back-pressure saturated specimens at initial effective vertical stresses of 50, 100, and 200 kPa. The tests were performed under undrained conditions with a horizontal displacement rate of 0.1 mm/min, equivalent to a constant shear strain rate of about 0.2%/min.

3. Results

3.1. Monotonic behaviour

Monotonic results of shear stress versus shear strain curves are presented with positive axes. According to some authors (e.g., Hanzawa 1980; Marcuson et al. 1990; Lade 1993; Lade and Yamamuro 1997; Yoshimine et al. 1999; Yamamuro and Covert 2001), a very loose specimen usually behaves contractively from the beginning of loading until reaching the final ultimate residual deviator stress in the effective stress path representation. The observed material behaviour was as expected for conventional geotechnical materials. The silty matrix with high void ratio, under undrained simple shear loading conditions, presented no pronounced peak strength on all three tests under distinct initial vertical effective stress. For initial effective vertical stresses of 50 kPa, 100 kPa and 200 kPa the shear stress increased to a level below 12, 23 and 36 kPa, respectively, which remained up to 30% of deformation, as demonstrated in the Fig. 4. Alongside the strength gain, pore pressure increased around 60% of the vertical effective stress until the end of the test, establishing no tendency of triggering static liquefaction. Similar trends were observed by Festugato et al. (2013, 2015) for silty gold tailings.

Fig. 5 shows that with the initial effective vertical stress of 50 kPa, 100 kPa and 200 kPa, the sample pore-water pressure reached 30 kPa, 70 kPa and 145 kPa, respectively, exhibiting a contractive behaviour. Likewise, a similar tendency was reported by Reid et al. (2018) for reconstituted loose specimens of silt iron ore tailings, when submitted to a direct simple shear tests.

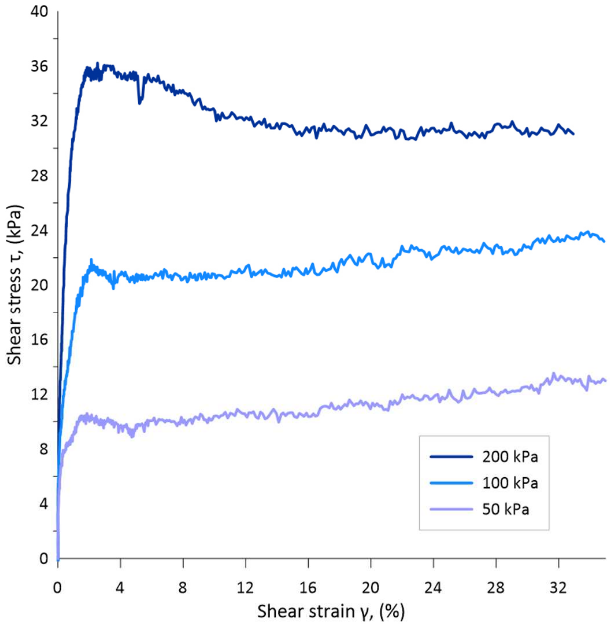

Figure 4. Stress-strain response in the Shear stress versus Shear strain plane.

The authors indicated that the tests were carried out under constant-volume conditions, with lateral restraint provided by a membrane surrounded by Teflon-coated rings. With the initial effective vertical stress of 150 kPa, the authors observed the sample shear stress rose to a level around 42 kPa exhibiting contractive behaviour. They also obtained a typical stress path of uncompacted fine materials under undrained shear conditions.

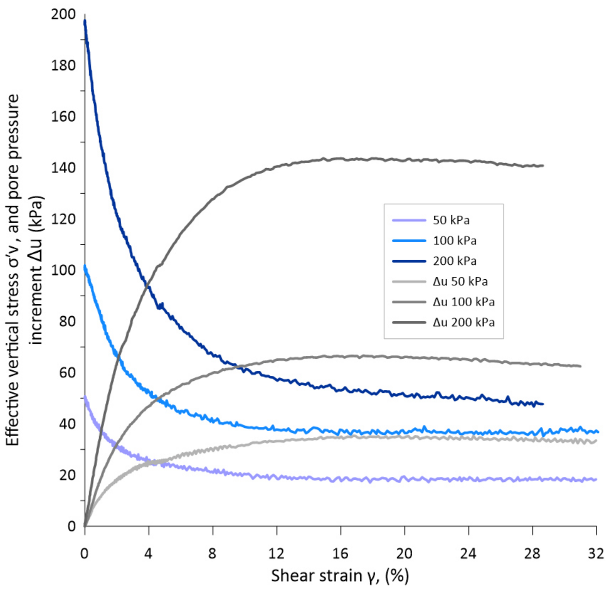

Figure 5. Effective vertical stress decrease and pore-water pressure variation versus shear deformation.

Fig. 6 presents the shear stress normalized by the vertical effective stress over shear strain, indicating a clear tendency of stabilization. Verdugo and Ishihara (1996) performed a series of CIU triaxial tests, where the samples were analysed with the same void ratio after consolidation and with different consolidation pressures. These experimental results showed that, for a given void ratio, the normalized undrained effective strength mobilized at large strains is unique regardless of the initial confining pressure. The authors concluded that it should be noted that, despite the large difference in the stress-strain behaviour at an early stage of loading, samples tend to have the same ultimate strength at a large level of deformation. In this research, it was observed a tendency of stabilizing the ratio (τ/σ'_v) into a value around 0.6, suggesting the very beginning of the "residual strength", as showed by Skempton (1985) and Verdugo and Ishihara (1996).

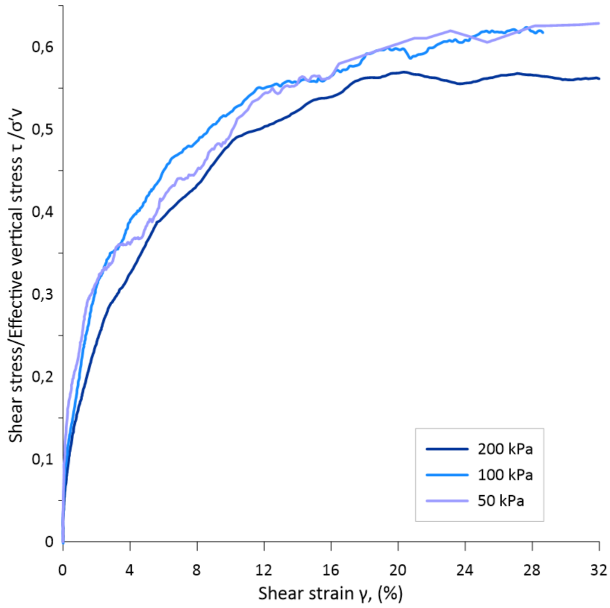

Figure 6. Normalized undrained effective strength behaviour versus Shear strain.

Fig. 7 presents the deviatoric stress versus the mean effective stress of the monotonic tests. Analysing the curves, an easily identifiable tendency in the *p' - q* plane is observed, similar to what was demonstrated by Reid et al. (2018) for an iron ore tailing under the DSS test.

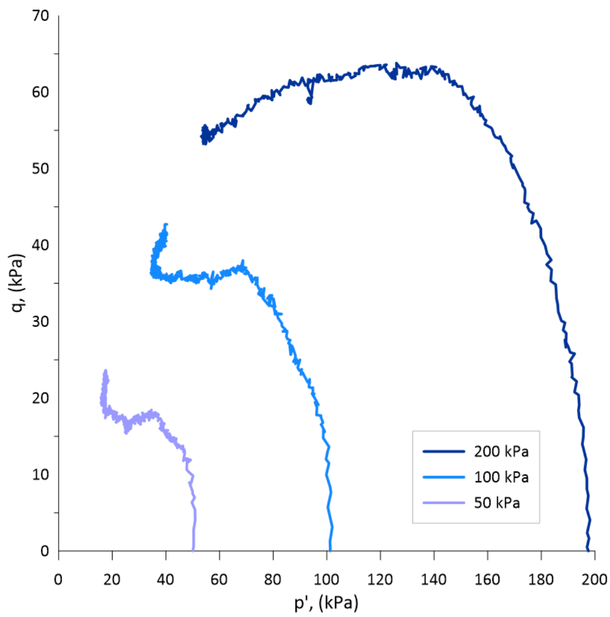

Figure 1. Stress path of the invariants *p'- q*, in the deviatoric stress versus mean effective stress plane.

3.2. Stress paths and strength envelopes

Fig. 8 shows the strength paths of the monotonic tests. The slope of the strength envelope indicates the friction angle, whereas its intersection with the ordinate axis, gives the exact cohesive intercept, both values of major importance for geotechnical applications. In this research, the effective friction angle of the material was 33.2º and the cohesive intercept null. Results of laboratory tests with iron ore tailings indicates a range, for dense samples, of friction angles between 34º to 39º (Hu et al. 2017, Li and Coop 2019, Consoli et al. 2022 and Velten et al. 2022).

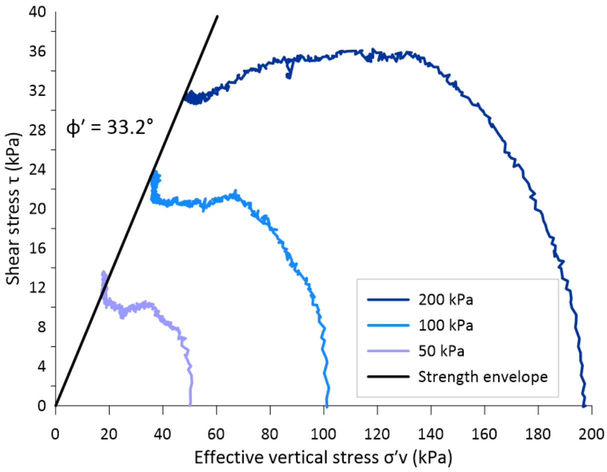

Figure 2. Stress path and strength envelope for the monotonic simple shear tests.

4. Conclusions

From the results of a series of monotonic simple shear tests carried out on iron mine tailings, the following conclusions could be drawn:

- Under the initial vertical effective stress range and conditions of this research (50, 100 and 200 kPa), specimens did not present liquefaction tendency. Even though the effective vertical stress never reached values approximated to zero, the samples tested were in a loose state and presented contractive behaviour (positive excess of pore-water pressure), so the material in these conditions must be treated with caution.
- A typical loose geotechnical material shear response was appreciated. No remarkable strength peaks were observed and a continuous asymptotic increase of pore pressure during shearing was presented. Shear stress was proportional to effective vertical stress.
- Normalized shear stress presented itself as a unique trend over shear strain.
- The same strength envelope was found for the studied stresses range, as expected. The effective friction angle of the material was 33.2º and the cohesive intercept was null.

Acknowledgements

The authors are grateful for the financial support provided by VALE S.A. (IAP-001247 and IAP-001466) and CNPq (Brazilian Research Council).

References

Aleshin, E. 1978. Comments on Utilization of Mining and Mineral Wastes. Proceedings of the 6th Mineral Waste Utilization Symposium. Co-sponsored by the U.S. Bureau of Mines and IIT Research Institute. Chicago, Illinois.

ASTM (2014) Standard test methods for specific gravity of soil solids by water pycnometer. D854. ASTM International, West Conshohocken, Pennsylvania, USA. 7

ASTM (2017a) Standard practice for classification of soils for engineering purposes (Unified Soil Classification System). D2487. ASTM International, West Conshohocken, Pennsylvania, USA. 10

ASTM (2017b) Standard test methods for liquid limit, plastic limit, and plasticity index of soils. D4318. ASTM International, West Conshohocken, Pennsylvania, USA. 20

ASTM (2017c) Standard test method for particle-size distribution (gradation) of fine-grained soils using the sedimentation (hydrometer) analysis. D7928. ASTM International, West Conshohocken, Pennsylvania, USA. 25

ASTM (2017d) Standard test methods for minimum index density and unit weight of soils and calculation of relative density. D4254. ASTM International, West Conshohocken, Pennsylvania, USA.

Bastos, L.A.C., Silva, G.C.S., Mendes, J.C., Peixoto, R.A.F. Using iron ore tailings from tailings dams as road material, J. Mater. Civ. Eng. 28 (2016), https://doi.org/10.1061/(ASCE)MT.1943-5533.0001613.

Boulanger, R. W., Chan, C. K., Seed, H. B., Seed, R. B., and Sousa, J. B., "A Low-Compliance Bi-Directional Cyclic Simple Shear Apparatus," Geotechnical Testing Journal, GTJODJ, Vol. 16, No. 1, March 1993, pp. 36-45.

Budhu, M. (1988). A new simple shear apparatus. Geotechnical Testing Journal. Vol. 11, No. 4, pp. 281-287, DOI: 10.1520/GTJ10660J.

Carneiro, A., Fourie, A. 2020. Assessing the impacts of uncertain future closure costs when evaluating strategies for tailings management, J. Clean. Prod. 247, 119173, https://doi.org/10.1016/j.jclepro.2019.119173.

Consoli, N.C.; Vogt, J.C.; Silva, J.P.S.; Chaves, H.M.; Scheuermann Filho, H.C.; Moreira, E.B.; Lotero, A. Behaviour of compacted filtered iron ore tailings–Portland cement blends: New Brazilian trend for tailings disposal by stacking. Appl. Sci. 2022, 12, 836, https://doi.org/10.3390/app12020836

Corte, M.B., Festugato, L., Consoli, N.C. 2017. Development of a cyclic simple shear apparatus. Soils and rocks. Volume 40, N. 3, September-December, https://doi.org/10.28927/SR.403279

Davies, M. 2011. Filtered Dry Stacked Tailings: The Fundamentals, University of British Columbia, Vancouver.

Festugato, L., Consoli, N. C. & Fourie, A. 2015. Cyclic shear behaviour of fibre-reinforced mine tailings. Geosynthetics International, 22, No. 2, 196–206. http://dx.doi.org/10.1680/gein.15.00005

Festugato, L., Fourie, A. and Consoli, N. C. 2013. Cyclic shear response of fibre-reinforced cemented paste backfill. Géotechnique Letters 3, 5–12, http://dx.doi.org/10.1680/geolett.12.00042

Fundação Estadual do Meio Ambiente (FEAM); Inventário de resíduos sólidos da mineração: Ano base 2017. Belo Horizonte, 2018, p. 47.

Hanzawa H. 1980. Undrained strength and stability analysis for a quick sand. Soils and Foundations, 20(2): 17–29.

Hu et al. 2017. Geotechnical Properties of Mine Tailings. Journal of Materials in Civil Engineering. 29 (2). http://dx.doi.org/10.1061/(ASCE)MT.1943-5533.0001736.

Jewell, R.J. & Fourie, A.B. 2015. Paste and thickened tailings – A guide, 3rd ed., Australian Centre for Geomechanics, Australia.

Ladd, R.S. 1978. Preparing test specimens using undercompaction. Geotech Test J 1(1):16–23

Lade P.V. & Yamamuro J.A. 1997. Effects of nonplastic fines on static liquefaction of sands. Canadian Geotechnical Journal, 34(6): 918–928.

Lade P.V. 1993. Initiation of static instability in the submarine Nerlerk berm. Canadian Geotechnical Journal, 30(6): 895–904.

Li, S., Chen, Q., Wang, X. 2016. Superiority of filtered tailings storage facility to conventional tailings impoundment in southern rainy regions of China, Sustainability 8 (11) 1130, https://doi.org/10.3390/su8111130

Li, W. and Coop, M.R. 2019. Mechanical behaviour of Panzhihua iron tailings. Canadian Geotechnical Journal. 56(3): 420-435, https://doi.org/10.1139/cgj-2018-0032.

Mao X, Fahey M. Behaviour of calcareous soils in undrained cyclic simple shear. Géotechnique 2003;53(8):715–27.

Marcuson W.F. III, Hynes M.E., and Franklin A.G. 1990. Evaluation and use of residual strength in seismic safety analysis of embankments. Earthquake Spectra, 6(3): 529–572.

Morgenstern, N.R.; Vick, S.G. & Zyl, D.V. 2015. Independent expert engineering investigation and review panel - Report on Mount Polley tailings storage facility breach. Government of British Columbia, Victoria, 147 p.

Morgenstern, N.R.; Vick, S.G.; Viotti, C.B. & Watts, B.D. 2016. Fundão tailings dam review panel - Report on the immediate causes of the failure of the Fundão dam. Fundão Tailings Dam Review Panel, [s.l.], 66 p.

Reid, D. et al. 2018. Characterisation of a subaqueously deposited silt iron ore tailings. Géotechnique Letters 8, 278–283, https://doi.org/10.1680/jgele.18.00105

Robertson, P.K.; de Melo, L.; Williams, D.J. & Wilson, G.W. 2019. Report of the expert panel on the technical causes of the failure of Feijão Dam I. Expert Panel, [s.l.], 71 p.

Salgado, R., Bandini, P., and Karim, A., 2000. Shear Strength and Stiffness of Silty Sand. J. Geotech. Geoenviron. Eng., Vol. 126, No. 5, pp. 451–462.

Schaper, D., Lessa, R., Freitas, A., Weeks, B. 2020. De-characterization and closure of TSF: concepts of the Brazilian legislation and international criteria. In Planning for closure 2020, 3rd International Congress on Planning for Closure of Mining Operations 499 (Chapter 6). Gecamin Digital Publications.

Skempton, A. W. (1954). The pore-pressure coefficients A and B. Géotechnique 4, No. 4, 143–147.

Skempton, A.W. 1985. Residual strength of clays in landslides, folded strata and the laboratory. Géotechnique, vol, 35, nº 1, p. 3-18.

Velten, R.Z., Consoli, N.C., Scheuermann Filho, H.C., Wagner, A.C., Schnaid, F., da Costa, J.P.R. 2022. Influence of grading and fabric arising from the initial compaction on the geomechanical characterisation of compacted copper tailings. Géotechnique. https://doi.org/10.1680/jgeot.22.00087

Verdugo, R. and Ishihara, K. 1996. The steady state of sandy soils. Soils and Foundations. Vol.36, no. 2, 81-91, Japanese Geotechnical Society, June.

Villet WCB, Sitar N, Johnson KA. Simple shear tests on highly overconsolidated offshore silts. In: Proceedings of the offshore technology conference, 6–9 May, Houston, USA, Paper No OTC 4918, 207-218; 1985.

Wijewickreme, D., Sanin, M. V. & Greenaway, R. G. 2005. Cyclic shear response of fine-grained mine tailings. Canadian Geotechnical Journal, 42, 1408–1421.

Wood, D., Drescher, A., & Budhu, M. (1979). On the Determination of Stress State in the Simple Shear Apparatus. *Geotechnical Testing Journal*, *2*(4), 211. https://doi.org/10.1520/GTJ10460J

Yamamuro J.A. & Covert K.M. 2001. Monotonic and cyclic liquefaction of very loose sands with high silt content. Journal of Geotechnical and Geoenvironmental Engineering, 127(4): 314–324.

Yoshimine M., Robertson P.K., & Wride C.E. 1999. Undrained shear strength of clean sands to trigger flow liquefaction. Canadian Geotechnical Journal, 36(5): 891–906.