On-site characterisation of compacted iron ore tailings-Portland cement blends for dry stacking systems

João Paulo de Sousa Silva[1], *Helder Mansur Chaves*[2], *Hugo Carlos Scheuermann Filho*[2#], and Nilo Cesar Consoli[2]

[1] *VALE S.A, Exploration and Mineral Projects Mineral Development Centre, Santa Luzia-MG, Brazil*
[2] *Universidade Federal do Rio Grande do Sul, Graduate Program in Civil Engineering, Porto Alegre-RS, Brazil*

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

ABSTRACT

Dry stacking of filtered tailings has become feasible due to the development of novel dewatering technologies. It offers an alternative to address the safety-related issues associated with conventional slurry disposal in reservoirs confined by upstream heightened dams. The operation and maintenance of such structures are challenging because of the high degree of uncertainty inherent in this material due to its spatial variability in state and gradation. It is also susceptible to liquefaction when saturated and in a loose state. In contrast, the filtered tailings can be compacted and piled up to hundreds of meters to meet prescribed design requirements. Eventually, a cementing agent can be incorporated into the tailings before compaction to enhance the general engineering properties. Nevertheless, few dry-stack facilities operate; none use cement as a stabilising agent. Accordingly, this paper assesses the mechanical response of artificially cemented iron ore tailings compacted in the field to form an experimental pile. Plate load tests and cone penetration tests were used. The experimental pile was divided into four sections, each compacted with different combinations of roller passes (4 or 6 passes) with and without vibration frequency. The results showed that the compacted material was practically insensitive to variations in compaction parameters, as evidenced by similar results in the tested sections' stress-strain responses and cone tip strength values. This study also highlights the effectiveness of field testing in investigating the response of stacking plants and the importance of using a small amount of cement to achieve adequate mechanical performance.

Keywords: iron ore tailings, filtered tailings, dry stacking of filtered tailings

1. Introduction

Stacking compacted filtered tailings to form piles is now an alternative to overcome safety-related issues related to the traditional slurry disposal in reservoirs, especially those contained by upstream heightened dams (Chaves et al., 2023; Gomes et al., 2016). In these, the raising dam is supported on the deposited material, which may be saturated and loose, thus prone to liquefy (Ledesma et al., 2022) . Therefore, it is unsurprising that most recent disasters involving tailings dams occurred on upstream heightened structures (Lyu et al., 2019; Palmer, 2019).

Dry stacking facilities present a shortened risk of physical instability because they comprise an unsaturated cake derived from a dewatering process compacted to prescribed design characteristics (Lupo and Hall, 2010). In other words, different from the tailings contained in reservoirs, the filtered material is well-characterized and promptly traceable within the piles structure. Occasionally, a small amount of cement can be incorporated into the tailings before compaction, aiming to improve the overall mechanical properties of the dry stacking facility (Bruschi et al., 2023; Consoli et al., 2022; Mafessoli et al., 2023). Still, understanding artificially cemented tailings' on-field behaviour is mandatory to design such novel structures adequately.

This is particularly important considering the Brazilian context, where the national regulatory agencies brought up novel regulations disallowing the construction of new upstream dams and demanding the closure of the existing ones (Schaper et al., 2020). As a reason there is an urgent need to handle the upcoming tailings (and the stored tailings from the past decades) since Brazil has been one of the top world iron ore producers (Vilaça et al., 2022), particularly considering the Quadrilátero Ferrífero region (province of Minas Gerais). Thus, Dry stacking appears to be a viable option.

Accordingly, this paper assesses the mechanical response of artificially cemented iron ore tailings compacted in the field to form an experimental pile. Plate load tests and cone penetration tests were used. The experimental pile was divided into four sections, each compacted with different combinations of roller passes (4 or 6 passes) with and without vibration frequency.

2. Experimental Program

The experimental program consists of three stages. The first involves the geotechnical characterisation of the filtered iron ore tailings (IOT). The second involves the construction of the experimental pile formed by artificially cemented IOT. The third, the most important, involves conducting the on-field tests to evaluate the material's performance after a 90-day curing period.

2.1. Materials

All the iron ore tailings (IOT) utilised herein derive from the same batch of dewatering/filtering processes of a plant in the Quadrilátero Ferrífero region. The material is the product of two different phases of the dewatering process: 80% (by dry mass) of a coarser material from the flotation phase and 20% (by dry mass) of a finer material from the hydrocyclone separation. Table 1 summarises the main physical characteristics of the IOT, which is classified as inorganic silt per the Unified Soil Classification System (ASTM, 2017). Mineralogically, this IOT mainly presents quartz and hematite. Chemically, it is mainly composed of silicon (70%), iron (24%), and aluminium (5%). A commercially available high-early Portland cement (type-III) was used as the cementing agent. The specific gravity of the cement grains is 3.15.

Table 1. Physical properties of the iron ore tailings

Characteristic	Iron ore tailings	Test method
Liquid limit (%)	-	
Plastic limit (%)	-	ASTM D4318
Plastic index (%)	non-plastic	
Specific gravity	3.08	ASTM D854
Coarse Sand (2.00 mm < *d* < 4.75 mm) (%)	0.0	
Medium Sand (0.425 mm < *d* < 2.00 mm) (%)	0.0	
Fine Sand (0.075 mm < *d* < 0.425 mm) (%)	48.0	ASTM D7928
Silt (0.002 < *d* < 0.075 mm) (%)	48.3	
Clay (*d* < 0.002 mm) (%)	3.70	
Effective diameter (D_{10}) (mm)	0.1	
Maximum dry unit weight at standard effort (kN/m³)	19.6 (*w* = 11.4%)	ASTM D698
Maximum dry unit weight at modified effort (kN/m³)	21.0 (*w* = 9%)	ASTM D1557

2.2. Methods

2.2.1. Dosage setup

A set of unconfined compressive strength tests supported the definition of the dosage characteristics (i.e., dry density, moisture content, and amount of cement) for the construction of the experimental piles. Eight different dosages were evaluated (in triplicates) considering the combination of two dry unit weight values (γ_d = 19.60 kN/m³ and γ_d = 20.05 kN/m³) and four cement contents (*C* = 1.5, 2.5, 3.5, and 4.5%). Succeeding, a unique representative dosage (γ_d = 19.60 kN/m³ and *C* = 2.5%) was chosen to construct the experimental pile. It corresponds to the optimum condition considering the standard compaction effort of the Proctor test and achieved a mean unconfined compressive strength of 900 kPa at 28 days of curing. Field-retrieved specimens (compacted at similar conditions) reached a mean unconfined compressive strength of around 800 kPa after 28 days of curing but with a greater scatter, mainly because of dry density variations (Chaves et al., 2023).

2.2.2. Experimental pile construction

The experimental pile is a structure composed of 5 layers of artificially cemented iron ore tailings. Each layer was attempted to be compacted to specific design requirements (same target γ_d = 19.60 kN/m³ but with different moisture contents) considering individual heights of 0.5 m. The pile is around 2.5 m in height, 16 m long and 18 m wide. Herein, the first two layers (from top to bottom) were investigated using the cone penetration tests (CPT), whereas the plate load test occurred at the top of the first layer. The first layer was compacted using the optimum moisture content (w_{opt} = 11.4%), and the layer below it used a moisture content 2% above this optimum value. Considering each layer construction, the selected amount of cement (*C* = 2.5%), iron ore tailings, and water were mixed in a soil-cement mixing plant at the experimental field. Right after, the material was collected (Fig. 1a), disposed of (Fig. 1b), spread (Fig. 1c), and levelled with the aid of a bulldozer. Then, the compaction occurred using a vibratory roller compactor (Fig. 1d) according to the compaction specifications related to the number of roller passes (P) and vibration frequency (VF). Each layer comprises four parallel sections (2.3 m wide and 16 m long), each with specific compaction specifications as follows: section I (4P and 35 Hz vibration), section II (6P and 35 Hz), section III (6P without vibration), and section IV (4P without vibration).

Figure 1. Construction of the experimental piles: (a) tailings collection, (b) deposition of the tailings, (c) spread of the tailings, and (d) compaction.

2.2.3. Cone penetration test (CPT)

Four CPT tests were conducted at the top of the experimental pile, considering each section, and reached depths corresponding to the second layer. A fully automated CPT apparatus was used to measure the tip resistance (q_c) and sleeve friction resistance (f_s) resulting from penetrating the apparatus at a constant rate of 20 mm per second.

2.2.4. Plate load test (PLT)

The plate load tests were conducted according to the recommendations stated by NBR 6489 (ABNT 2016). The load was applied in equal increments (of not more than one-tenth of the estimated ultimate bearing capacity) to a circular rigid steel plate (300 mm diameter – Fig. 2a) using a hydraulic jack (Fig. 2b) coupled to a reaction system (a 20000 kgf center-pivot backhoe loader – Fig. 2d). The applied load was digitally monitored through a load cell. For each increment, settlement measurements were electronically registered at specified moments (0, 0.25, 0.5, 1, 2, 4, 8, 15, 30, and 60 min) using four linear potentiometers fixed at a reference beam (Fig 2c).

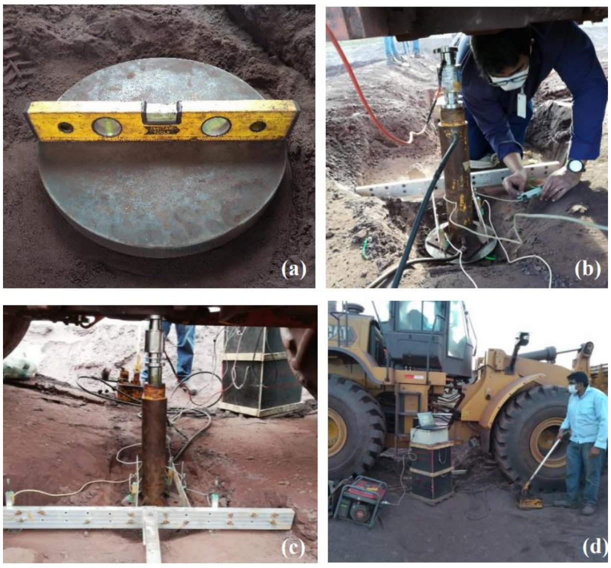

Figure 2. Conduction of the PLTs (a) circular plate (b) test setup (c) reference beam (d) reaction system.

3. Results

3.1. Cone penetration tests

Fig. 3 depicts the CPT test data. Due to the high resistance of the cemented layer, the CPT apparatus could not penetrate more than 0.3 meters within the pile. Only the top layer of the experimental pile could be investigated. Overall, comparable q_c values were reported for all the tested sections, regardless of their compaction characteristics. The CPT assessment could not capture the influence of the number of roller passes and the usage of a vibration frequency. In contrast, the reported f_s values were slightly more variable, but this analysis is compromised due to the short penetration depth.

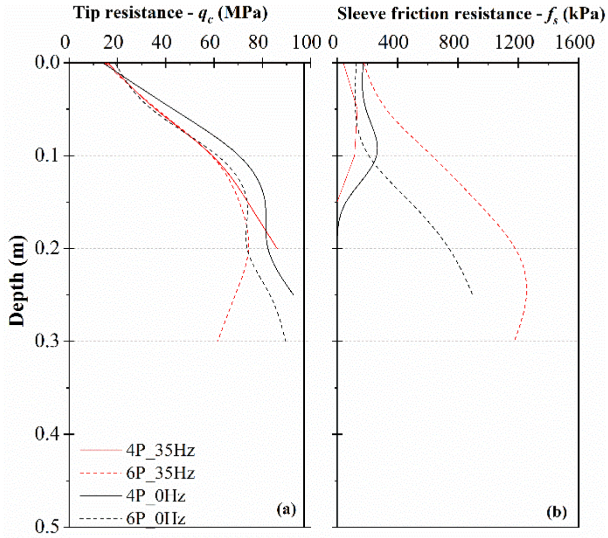

Figure 3. CPT data (a) tip resistance (b) sleeve friction resistance.

3.2. Plate load tests

Fig. 4 presents the vertical displacement (δ) versus the applied vertical stress (σ_v) for each plate load test. As observable, the tests did not reach (and were far from reaching) the failure/ultimate load of the cemented iron ore tailings, which indicates the high resistance of the cemented iron ore tailings. In other words, the tests ended because of the limiting capacity of the reaction system. Still, the sections compacted using a vibration frequency of 35 Hz were slightly stiffer, particularly for vertical stresses above 900 kPa. It also seems that passing the roller four times is sufficient to guarantee the proper compaction, and thus an adequate response, of the layer. Essentially, however, the four different sections presented very similar load-displacement responses, considering the applied load range. Table 2 presents the stiffness data considering a secant modulus (E_{sec}), calculated using Eq. (1), and a tangent modulus (E_{tan}), which was determined up to the first load increment. For using Eq. (1), the medium is considered homogeneous, the shape factor (C_s) equal to 0.70, and the Poisson ratio (υ) equal to 0.30, which is adequate for drained loading conditions (Fang, 1991).

$$E_{sec} = \frac{\sigma_v \cdot D \cdot C_s}{\delta}(1 - \upsilon^2) \quad (1)$$

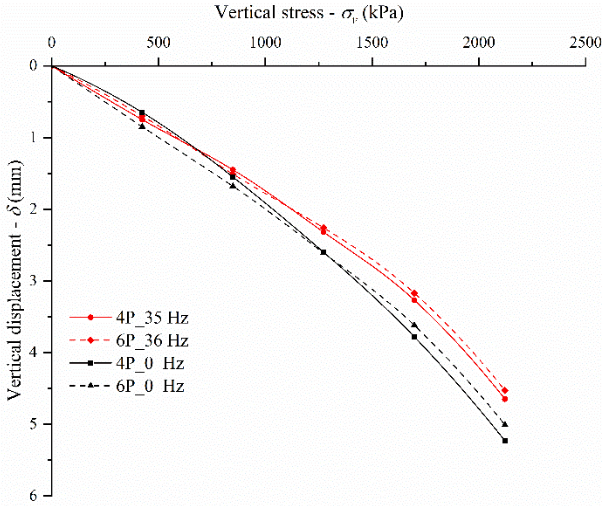

Figure 4. Plate load test data.

Table 2. Plate load test data

Material	σ_v (MPa)	δ (mm)	E_{sec} (MPa)	E_{tan} (MPa)
4P-35 Hz	424	0.75	118	118
	848	1.45	122	
	1273	2.32	115	
	1697	3.28	108	
	2122	3.65	95	
6P-35 Hz	424	0.70	127	127
	848	1.51	118	
	1273	2.26	118	
	1697	3.14	113	
	2122	4.53	98	
4P-0 Hz	424	0.65	137	137
	848	1.62	110	
	1273	2.68	99	
	1697	3.78	94	
	2122	5.28	84	
6P-0 Hz	424	0.85	127	127
	848	1.68	106	
	1273	2.61	102	
	1697	3.62	98	
	2122	5.01	89	

Considering the four different sections, all the reported stiffness values are comparable (are of the same order of magnitude). Still, the sections compacted using a 35 Hz vibration frequency appeared slightly stiffer at the latter load increments, which may be related to the fabric and the achieved dry density.

4. Conclusions

This paper concerned the on-field analysis of an experimental pile formed by compacted artificially cemented iron ore tailings. For this, cone penetration tests (CPT) and plate load tests (PLT) were carried out at the top of the experimental pile. These tests were conducted in four sections, each compacted with different characteristics: number of rollers passes (4 or 6) and usage/absence of a 35 Hz vibration frequency. The CPT data did not show remarkable differences between the four sections, and due to the layer's resistance, it could not penetrate more than 0.3 meters in depth. This demonstrates that such a test is inappropriate for evaluating artificially cemented materials' on-field mechanical response. Despite being far from the failure load, the PLT responses were similar amongst the four sections but slightly stiffer when vibration frequency was used in the compaction process. Using vibration probably resulted in a fabric favouring the material's mechanical response. Essentially, the results presented herein demonstrate the high resistance of the artificially cemented iron ore tailings, making them suitable as an alternative to the traditional slurry disposal in ponds. Still, further on-field testing is required as the CPT did not appear adequate for characterising such a material.

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References

ASTM, 2017. Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System) - ASTM D2487. ASTM International. https://doi.org/10.1520/D2487-17E01

Bruschi, G.J., Santos, C.P.D., Filho, H.C.S., Da Silva Martinatto, C., Schulz, L.R., Silva, J.P.D.S., Consoli, N.C., 2023. Mechanical and Microstructural Response of Iron Ore Tailings under Low and High Pressures Considering a Wide Range of Molding Characteristics. Mining 3, 712–730. https://doi.org/10.3390/mining3040039

Chaves, L.R.D.C., Heineck, K.S., Scheuermann Filho, H.C., Chaves, H.M., Carvalho, J.V.D.A., Wagner, A.C., Silva, J.P.D.S., Consoli, N.C., 2023. Field and laboratory study of iron ore tailings–Portland cement blends for dry stacking. Proc. Inst. Civ. Eng. - Geotech. Eng. 1–10. https://doi.org/10.1680/jgeen.23.00097

Consoli, N.C., Vogt, J.C., Silva, J.P.S., Chaves, H.M., Scheuermann Filho, H.C., Moreira, E.B., Lotero, A., 2022. Behaviour of Compacted Filtered Iron Ore Tailings–Portland Cement Blends: New Brazilian Trend for Tailings Disposal by Stacking. Appl. Sci. 12, 836. https://doi.org/10.3390/app12020836

Fang, H.-Y. (Ed.), 1991. Foundation Engineering Handbook. Springer US, Boston, MA. https://doi.org/10.1007/978-1-4757-5271-7

Gomes, R.B., De Tomi, G., Assis, P.S., 2016. Iron ore tailings dry stacking in Pau Branco mine, Brazil. J. Mater. Res. Technol. 5, 339–344. https://doi.org/10.1016/j.jmrt.2016.03.008

Ledesma, O., Sfriso, A., Manzanal, D., 2022. Procedure for assessing the liquefaction vulnerability of tailings dams. Comput. Geotech. 144, 104632. https://doi.org/10.1016/j.compgeo.2022.104632

Lupo, J.F., Hall, J.E., 2010. Dry stack tailings – design considerations.

Lyu, Z., Chai, J., Xu, Z., Qin, Y., Cao, J., 2019. A Comprehensive Review on Reasons for Tailings Dam Failures Based on Case History. Adv. Civ. Eng. 2019, 1–18. https://doi.org/10.1155/2019/4159306

Mafessoli, M., Marques, S.F.V., Scheuermann Filho, H.C., Consoli, N.C., 2023. Response of Artificially Cemented Iron Ore Tailings for Dry Stacking Disposal over a Wide Range of Stresses. Indian Geotech. J. https://doi.org/10.1007/s40098-023-00711-w

Palmer, J., 2019. Anatomy of a Tailings Dam Failure and a Caution for the Future. Engineering 5, 605–606. https://doi.org/10.1016/j.eng.2019.07.009

Schaper, D., Lessa, R., Freitas, A., Weeks, B., 2020. De-characterization and closure of TSF: concepts of the Brazilian legislation and international criteria. Presented at the Planning for closure 2020, Gecamin Digital Publications, virtual format.

Vilaça, A.S.I., Simão, L., Montedo, O.R.K., Novaes de Oliveira, A.P., Raupp-Pereira, F., 2022. Waste valorization of iron ore tailings in Brazil: Assessment metrics from a circular economy perspective. Resour. Policy 75, 102477. https://doi.org/10.1016/j.resourpol.2021.102477