Assessment of the Hydraulic Properties of Iron Ore Tailings for Mining Closure Projects in Brazil

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ABSTRACT:
Recent disasters with tailings dams raised by the upstream method have resulted in modifications to the legislation regarding tailings disposal. New regulations require these structures to be properly decommissioned. Closure projects require changes in the original structure to increase safety and reduce risk. This safer condition is usually achieved by removing materials from the original dam. These materials, afterward, can be stored as dry stacks using filtered and compacted materials. The materials in stacks will usually be unsaturated. Also, the use of dry stacking has been successfully addressed for arid areas for a long but lacks more data for structures in tropical climate areas. This study focused on assessing the hydraulic properties of three types of tailings (named A, B, and C) collected from a tailings' impoundment in Brazil at distinct stages of saturation. Then, permeability tests were performed using a flexible wall permeameter in different stages of degree of saturation, starting from 100%, considering the conditions of the tailings dams, and then decreasing the degree of saturation to account for the unsaturated behavior of tailings in dry stacks. The diffusivity, volumetric water content, and hydraulic conductivity of the tailings were studied and the changes in them showed similar trends for tailings B and C. However, tailings A exhibited some differences by displaying higher diffusivity and volumetric water content throughout the test, along with lower hydraulic conductivity, which remained relatively consistent during the entire test. Tailings A had the lowest saturated hydraulic conductivity as well.

KEYWORDS: Mining closure, tailings, permeability, hydraulic conductivity, volumetric water content, diffusivity.

1 INTRODUCTION

Tailings dams are generally constructed from local mining materials. The embankments can either be raised upstream, vertically (center-line) or downstream. Among these, upstream raising is the cheapest, hence, its construction became popular years ago (Kossoff et al., 2014). However, there are many failures reported in such dams for reasons like poor design and construction of primary dyke and drainage culverts (Consoli et al., 2022; Wei et al., 2013).

Owing to the numerous failures associated with the upstream dams, new regulations have been proposed in the Brazilian mining industry to enhance safety and mitigate risks. Thus, construction of new upstream raised dams was prohibited and those existing must be decommissioned. To achieve this goal, it is essential to safely decommission upstream tailings dams, highlighting the importance of comprehending the geotechnical properties of tailings, particularly focusing on hydraulic properties and permeability traits (Kütter et al., 2023).

Filtered tailings, also known as stacked tailings or dry stacked tailings, have gained popularity in recent years as an eco-friendly option compared to the traditional practice of depositing slurry in tailings dams. From a geotechnical perspective, the main advantage of stacked tailings lies in the dewatering process, which enables tailings to be disposed of with water content close to the optimum condition achieved in standard Proctor tests (Dias Neto et al., 2024). Nonetheless, as the moisture content of the tailings after dewatering can vary significantly due to the variability in grain size distribution and mineralogical composition, impacting the efficiency of the filtration process, the unsaturated hydraulic behavior of the tailings is crucial to be considered. Furthermore, a critical factor highlighted by Rissoli et al. (2023) is the strong influence of weather conditions, especially during the rainy season in the southeastern region of Brazil, on the final moisture content of the filtered material. Therefore, the tailings in stacks will most probably be found initially in unsaturated conditions.

Moreover, groundwater seepage characteristics play a crucial role in designing tailings storage facilities. The seepage rate is directly influenced by the hydraulic conductivity coefficient (Shaker et al., 2022). This parameter is influenced by factors such as the fines content, ore mineralogy, and material density (Lupo & Hall, 2010). Besides, seepage can trigger various phenomena in the tailings, such as soil flow, contact soil flow, piping, and contact scouring (Wang et al., 2021). Recently, studies have concentrated more on evaluating the hydromechanical behavior of the tailings due to their importance in tailings storage facilities (Alhomair et al., 2017; Shamsai et al., 2007; Singh et al., 2021). The average tailings hydraulic conductivity was shown to decrease with increasing fine content.

Studying the hydraulic properties of tailings can be very important because their hydromechanical properties play a crucial role in determining the layering, permeability, and compressibility of the tailings storage structure. Hence, this paper evaluates the hydraulic properties of three different tailings (A, B, and C) from a tailings' impoundment in Brazil, considering both saturated and unsaturated hydraulic behavior of tailings. This evaluation aims to address the important considerations regarding mining closure projects (the saturated tailings found in the existent dam) and the possible after-removal disposition of dry stacks (the tailings removed from the dam are filtered and disposed of in dry stacks).

2 MATERIALS AND METHODS

2.1 Iron ore tailings (IOTs)

The analyzed tailings were obtained from three distinct locations within a tailings' impoundment in Minas Gerais, Brazil. In this study, the tailings were non-plastic and classified as A, B, and C. The grain size distribution of the tailings is depicted in Figure 1, revealing that tailings A is the finest, with 86.9% silt and 11.4% clay content. Tailings B and C have silt contents of 63.3% and 23.7% and clay contents of 2.4% and 1.4%, respectively, based on which tailings C is characterized as the coarsest. These tailings exhibit non-plastic properties, with tailings A and B classified as ML and tailings C as SM according to the Unified Soil Classification System (USCS) (ASTM D2487, 2011). The specific gravities (G_s) of the tailings were measured as 3.71, 3.64, and 3.52 for types A, B, and C, respectively (ASTM D854, 2005). Table 1 also lists the dominant mineralogical compositions of the IOTs studied.

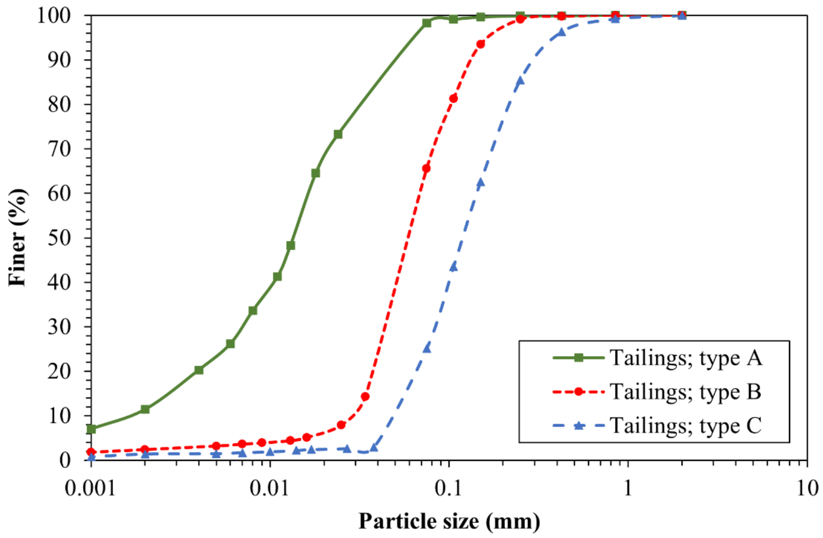

Figure 1 - Grain size distributions of the studied iron ore tailings.

Table 1 - Dominant mineralogical compositions of the studied IOTs.

Minerals		**Tailings A**	**Tailings B**	**Tailings C**
Silicates (%)	Quartz - SiO_2	21.98	47.63	48.08
	Chlorite	19.97	0.44	0.38
Oxides (%)	Iron Oxides	50.92	51.04	49.15

2.2 Permeability tests

A series of permeability tests were conducted on loosely compacted samples, targeting a relative density range of 30% to 50%. The minimum and maximum index densities were determined using ASTM D4254 (2006) and ASTM D4253 (2006), respectively (only for the maximum index of tailings A, the maximum dry density from a modified proctor (ASTM D1557, 2012) was considered). To replicate the high void ratios observed in the field, the samples were reconstituted using the moist-tamping method.

All the samples were fully saturated before starting the permeability tests, as confirmed by a B-value exceeding 0.97. The consolidation stress applied during the tests was approximately 100 kPa. The hydraulic conductivity test was performed using a flexible wall permeameter following ASTM D7664 (2018), Method B, which involves axis translation and refers to moving the sample in a specific direction during the test. An air entry pressure of 500 kPa was considered for the porous plate, indicating the pressure at which air begins to enter the porous material. De-aired water was used as the permeant, meaning that any dissolved air in the water was removed to prevent interference with the test results. The tests were conducted in six different stages where suction pressure was applied increasingly at 5, 10, 25, 50, 100, and 500 kPa at each specific step with the degree of saturation decreasing from a fully saturated condition (100%). Also, the changes in void ratios for tailings A, B, and C were initially measured, followed by measurements after consolidation and at the final step, as enlisted in Table 2.

Table 2 - Void ratio variations during testing of the studied IOTs.

Tailings	**Initial**	**Post-consolidation**	**Final**

Type A	1.66	1.46	1.46
Type B	0.81	0.76	0.76
Type C	0.74	0.72	0.72

3 PERMEABILITY TEST RESULTS

3.1 Volumetric water content

Figure 2 illustrates the changes in volumetric water content against suction increment during the test. As observed, with the increase in matric suction pressure across stages, the volumetric water content decreased in the various samples of tailings A, B, and C. This indicates that as the suction increment rises, the ability of the tailings to retain water decreases, resulting in a reduction in volumetric water content. These values almost reached zero for tailings B and C. It is essential to note that tailings A demonstrated a higher range compared to tailings B and C. Also, the trends in the changes for tailings B and C were similar. The volumetric water content started at 0.59, 0.43, and 0.42, and ended at 0.33, 0.01, and 0.02 for tailings A, B, and C, respectively. The decreasing trend in water content indicates that the tailings are drying out as suction pressure increases. These results are crucial as the a need to consider the variation in the degree of saturation under real field conditions.

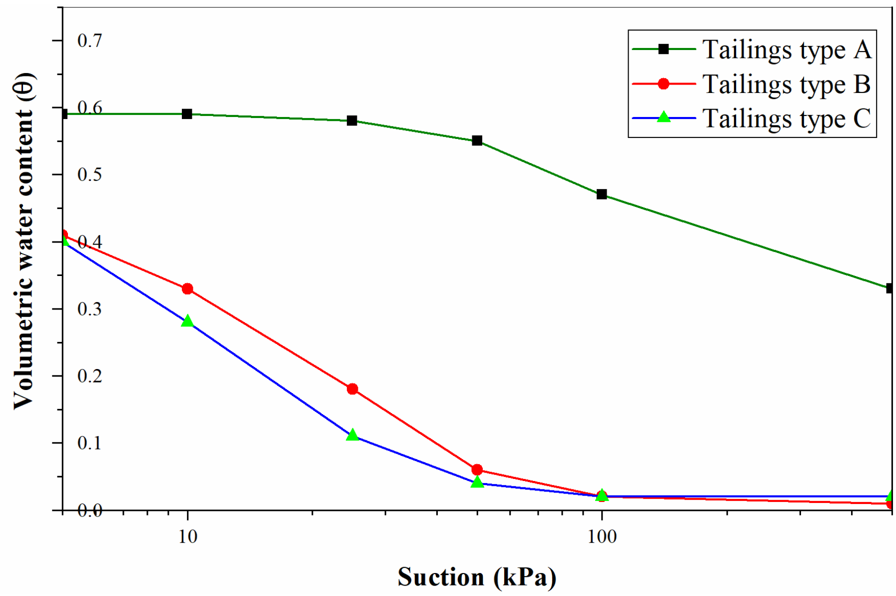

Figure 2 - Variation of volumetric water content against different suction pressures

3.2 Hydraulic conductivity

Figure 3 depicts the results of the hydraulic conductivity versus the changes in matric suction for the three studied tailings. From the graphs, it can be interpreted that the finer tailings (tailings A) exhibited a different behavior. The fluctuations in hydraulic conductivity are minimal for tailings A, with an average value of 7.02859E-11, which is extremely close to zero. Meanwhile, the characteristics of tailings B and C exhibited similarities. Initially, their values were 1.4E-09 and 2.0E-09, respectively. Having a decreasing trend, their final stage values are 1.8E-14 and 2.6E-15. Low hydraulic conductivity in tailings can limit the movement of water through the material, which may reduce the water infiltration in the structure. By incorporating fine contents that decrease hydraulic conductivity into the design of dry stacks, engineers can reduce the water infiltration and minimize the risk of seepage or failure of the structure.

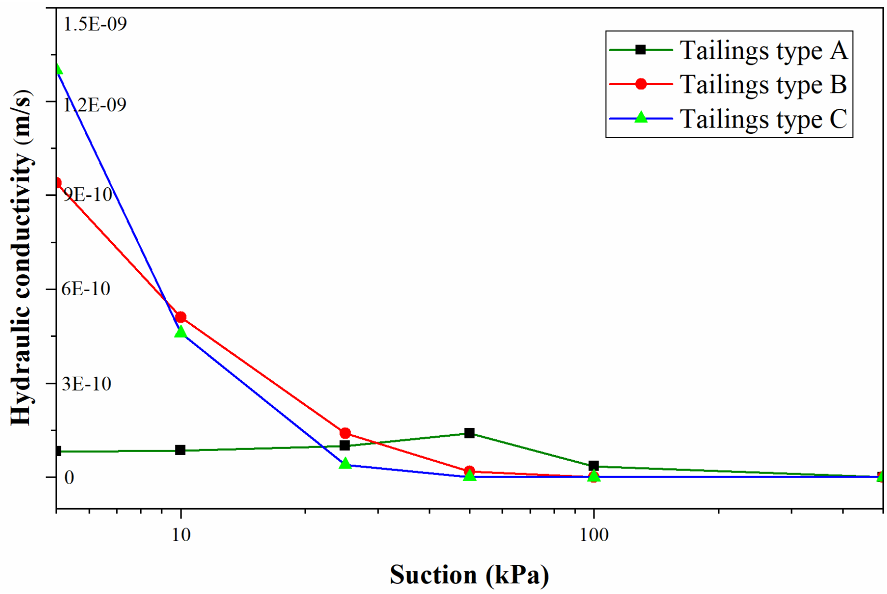

Figure 3 - Variation of hydraulic conductivity against different suction pressures

3.3 Diffusivity

Figure 4 displays the results of diffusivity versus the changes in matric suction for the three studied tailings. Diffusivity is a parameter dependent on both hydraulic conductivity and the volumetric water content-suction curve. It illustrates how water can move through the soil and how quickly the soil can retain or release water at various suction levels. Diffusivity can be calculated as the hydraulic conductivity divided by the gradient of the volumetric water content-suction curve (Gallage et al., 2013). Generally, diffusivity decreases with an increase in suction, and this reduction is more pronounced in tailings A, which has a higher fine content. The average values of diffusivity are 6.31E-09, 2.40E-09, and 1.53E-09 for tailings A, B, and C respectively. These values provide insights into how these specific types of tailings interact with water and influence water movement within them.

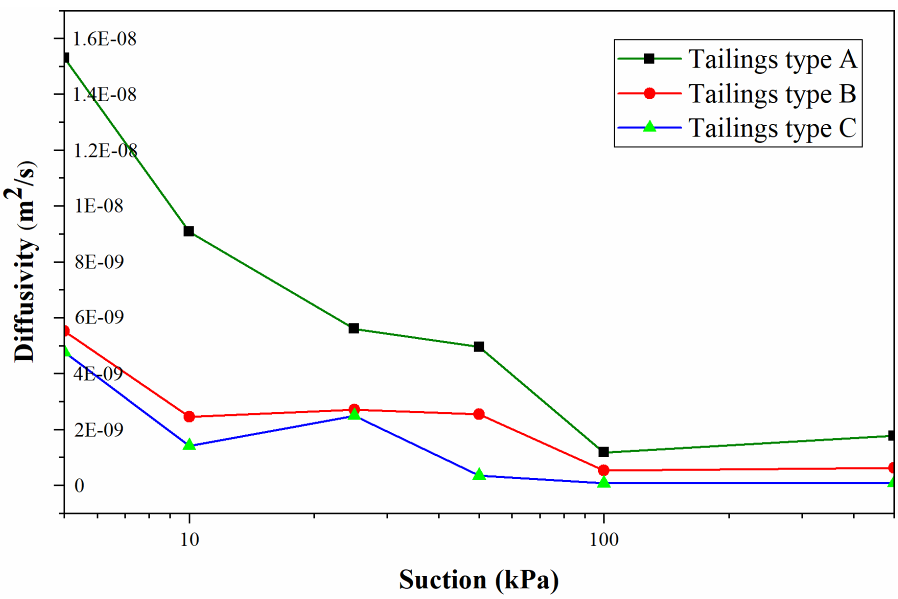

Figure 4 - Variation of diffusivity against different suction pressures

3.4 Saturated hydraulic conductivity

The saturated hydraulic conductivity was measured as investigating the worst-case scenario where the tailings are saturated on the dams. In the context of dry stacks, measuring the saturated hydraulic conductivity can help in predicting how water will flow through and interact with the tailings during heavy rainfall events. Figure 5 illustrates the changes in saturated hydraulic conductivity versus different tailings (A, B, and C) and the fine (silt and clay) contents of the tailings under investigation. Firstly, there was a clear increase in the saturated hydraulic conductivity from tailings A to C. Moreover, as the fine content of the tailings increased, the saturated hydraulic conductivity decreased. The saturated hydraulic conductivity ranged from 5E-11 to 2E-9. It is notable that tailings A, which possess the highest fine content, had the lowest saturated hydraulic conductivity. Conversely, tailings C, which are coarser with a lower fine content, have the highest saturated hydraulic conductivity.

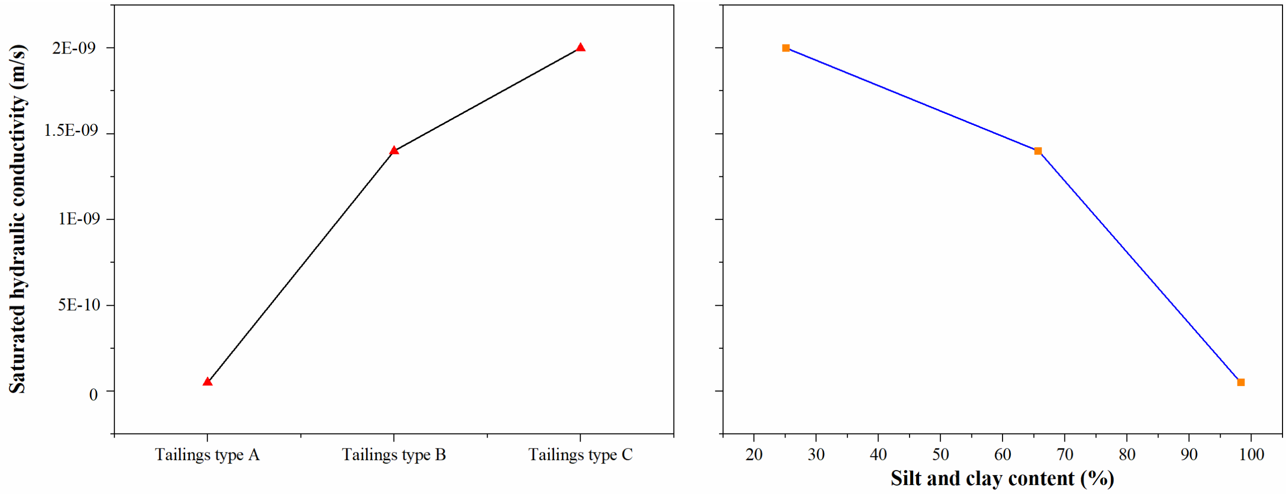

Figure 5 – Variations of saturated hydraulic conductivity versus different tailings (A, B, and C) and the fine (silt and clay) contents

4 CONCLUSIONS

This study examined the hydraulic behavior of three distinct tailings collected from a tailings storage facility in Brazil. Permeability tests were conducted to assess key properties, such as hydraulic conductivity, water content, and diffusivity, against the changes in the degree of saturation to consider the application of dry stacking, where unsaturated behavior is crucial. Additionally, the saturated hydraulic conductivity was discussed to consider the situation of tailings in tailings dams. The principal findings are summarized as follows.

- When considering the changes in volumetric water content at different suction pressures, tailings A showed a wider range than tailings B and C. The initial volumetric water content values were 0.59, 0.43, and 0.42, and they ended at 0.33, 0.01, and 0.02 for tailings A, B, and C, respectively. Higher values in tailings A may show that it has a higher capacity for retaining water compared to tailings B and C under varying suction pressures.
- The hydraulic conductivities were relatively low, with final stage values of 1.2E-15, 1.8E-14, and 2.6E-15 for tailings A, B, and C. This implies that the tailings are less likely to allow water to flow through them easily, which can be beneficial in terms of reducing the risk of seepage and water infiltration in dry stacking applications.
- The average diffusivity values were 6.31E-09, 2.40E-09, and 1.53E-09 for tailings A, B, and C.
- An increase in the fine content of the tailings resulted in a decrease in the saturated hydraulic conductivity. Fine particles (silt and clay) can clog pore spaces within the tailings material, reducing the ability of water to flow through the stacks.

Finally, the findings of this research contribute to a comprehensive understanding of the hydromechanical behavior of iron ore tailings (IOTs) aimed at decommissioning projects and construction of dry stacks, which generally show that the studied tailings are low-permeability materials.

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REFERENCES

Alhomair, S. A., Gorakhki, M. H., & Bareither, C. A. (2017). Hydraulic Conductivity of Fly Ash-Amended Mine Tailings. *Geotechnical and Geological Engineering*, *35*(1), 243–261. https://doi.org/10.1007/S10706-016-0101-Z/TABLES/4

ASTM D854. (2005). *"Standard Test Methods for Specific Gravity of Soil solids by Water Pycnometer", ASTM International, West Conshohocken, PA, 2005, DOI: 10.1520/D0854-05*. ASTM international.

ASTM D1557. (2012). Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft3 [2,700 kN-m/m3]) D1557 (2012). *Annual Book of ASTM Standards, ASTM International, West Conshohocken, PA.*

ASTM D2487. (2011). D2487 (2011) Standard practice for classification of soils for engineering purposes (Unified Soil Classification System). *ASTM International, West Conshohocken, PA, Www. ASTM. Org*.

ASTM D4253. (2006). *Standard test methods for maximum index density and unit weight of soils using a vibratory table. ASTM International, West Conshohocken, Pa*.

ASTM D4254. (2006). *Standard test methods for minimum index density and unit weight of soils and calculation of relative density. ASTM International, West Conshohocken, Pa*.

ASTM D7664. (2018). Standard test methods for measurement of hydraulic conductivity of unsaturated soils. *ASTM International* .

Consoli, N. C., Vogt, J. C., Silva, J. P. S., Chaves, H. M., Filho, H. C. S., Moreira, E. B., & Lotero, A. (2022). Behaviour of Compacted Filtered Iron Ore Tailings–Portland Cement Blends: New Brazilian Trend for Tailings Disposal by Stacking. *Applied Sciences 2022, Vol. 12, Page 836*, *12*(2), 836. https://doi.org/10.3390/APP12020836

Davies, M. (2011). *Filtered dry stacked tailings : the fundamentals*. https://doi.org/10.14288/1.0107683

Dias Neto, S. L. S., Ferraz, R. L., da Silva, T. O., Marques, E. A. G., Pitanga, H. N., & Cândido, E. S. (2024). Hydraulic Characteristics of Silt-Sized Iron Ore Tailings. *Geotechnical and Geological Engineering 2024*, 1–23. https://doi.org/10.1007/S10706-024-02755-Y

Gallage, C., Kodikara, J., & Uchimura, T. (2013). Laboratory measurement of hydraulic conductivity functions of two unsaturated sandy soils during drying and wetting processes. *Soils and Foundations*, *53*(3), 417–430. https://doi.org/10.1016/J.SANDF.2013.04.004

Kossoff, D., Dubbin, W. E., Alfredsson, M., Edwards, S. J., Macklin, M. G., & Hudson-Edwards, K. A. (2014). Mine tailings dams: Characteristics, failure, environmental impacts, and remediation. *Applied Geochemistry*, *51*, 229–245. https://doi.org/10.1016/J.APGEOCHEM.2014.09.010

Kütter, V. T., Martins, G. S., Brandini, N., Cordeiro, R. C., Almeida, J. P. A., & Marques, E. D. (2023). Impacts of a tailings dam failure on water quality in the Doce river: The largest environmental disaster in Brazil. *Journal of Trace Elements and Minerals*, *5*, 100084. https://doi.org/10.1016/J.JTEMIN.2023.100084

Lupo, J., & Hall, J. (2010). *Tailings and Mine Waste 2010 - Google Books*. In Proceedings Fourteenth International Conference on Tailings and Mine Waste (pp. 327-334).

Rissoli, A. L. C., Pereira, G. S., Mendes, A. J. C., Scheuermann Filho, H. C., Carvalho, J. V. de A., Wagner, A. C., Silva, J. P. de S., & Consoli, N. C. (2023). Dry Stacking of Filtered Iron Ore Tailings: Comparing On-Field Performance of Two Drying Methods. *Geotechnical and Geological Engineering*, 1–12. https://doi.org/10.1007/S10706-023-02689-X/FIGURES/8

Shaker, A. A., Dafalla, M., Al-Mahbashi, A. M., & Al-Shamrani, M. A. (2022). Predicting Hydraulic Conductivity for Flexible Wall Conditions Using Rigid Wall Permeameter. *Water 2022, Vol. 14, Page 286*, *14*(3), 286. https://doi.org/10.3390/W14030286

Shamsai, A., Pak, A., Bateni, S. M., & Ayatollahi, S. A. H. (2007). Geotechnical characteristics of copper mine tailings: A case study. *Geotechnical and Geological Engineering*, *25*(5), 591–602. https://doi.org/10.1007/S10706-007-9132-9/TABLES/6

Singh, S., Zurakowski, Z., Dai, S., & Zhang, Y. (2021). Effect of Grain Crushing on the Hydraulic Conductivity of Tailings Sand. *Journal of Geotechnical and Geoenvironmental Engineering*, *147*(12), 04021143. https://doi.org/10.1061/(ASCE)GT.1943-5606.0002667

Wang, G., Hu, B., Tian, S., Ai, M., Liu, W., & Kong, X. (2021). Seepage field characteristic and stability analysis of tailings dam under action of chemical solution. *Scientific Reports 2021 11:1*, *11*(1), 1–11. https://doi.org/10.1038/s41598-021-83671-6

Wei, Z., Yin, G., Wang, J. G., Wan, L., & Li, G. (2013). Design, construction and management of tailings storage facilities for surface disposal in China: Case studies of failures. *Waste Management and Research*, *31*(1), 106–112. https://doi.org/10.1177/0734242X12462281