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Influence of initial compaction and confining pressure on the hydraulic conductivity of compacted iron ore tailings

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ABSTRACT

The hydraulic conductivity of iron tailings is an important factor affecting the stability of tailings storage facilities. Stacking compacted filtered ore tailings is a promising alternative for safer tailings disposal. These tailings storage facilities' internal drainage systems must be designed appropriately to avoid excessive seepage pressure, saturation, and slope failure. In this context, the factors that affect hydraulic conductivity must be adequately evaluated. Therefore, the hydraulic conductivity behavior of compacted iron ore tailings still needs to be investigated. In addition, the effect of high confining pressure on hydraulic conductivity needs to be evaluated. This study investigates the impact of the initial compaction and the confining pressure on hydraulic conductivity. For this, the flexible wall permeameter tests were carried out on filtered ore tailings compacted in three degrees of compaction: 77, 94, and 101% of optimum dry density as determined by the standard Proctor method. These specimens were saturated and then consolidated with different confining pressure. It is possible to affirm that the increased confining pressure decreases the hydraulic conductivity. The hydraulic conductivity decreases by less than one order of magnitude, regardless of the initial compaction. Moreover, the data suggest that hydraulic conductivity's decay rate depends on initial compaction—the hydraulic conductivity of the loose specimen decays at a greater rate than that of the dense specimens. However, the reductions of the void ratio under the confining pressure of 1600 kPa and 2200 kPa were not enough to decrease the hydraulic conductivity. Thus, under high-stress confining, the hydraulic conductivity becomes practically constant.

Keywords: Iron ore tailings hydraulic behavior; Dry stack tailings; Compaction; Transitional behavior in tailings.

1. Instruction

Mining tailings are residues derived from ore extraction and processing, consisting mainly of crushed rock, water, and chemicals (Kossoff et al. 2014, Li et al. 2018). Large-scale mining processing generates many tailings worldwide (Yang et al. 2016). Usually, these materials have silt or sandy-sized particles and intermediate permeability (10^{-5} to 10^{-8} m/s), making it difficult to interpret them because they do not always follow the concepts established in the literature for sands and clays (Dienstmann et al. 2018, Schnaid 2020).

Tailings storage facilities (TSFs) are engineered structures constructed to impound slurry, thickened, and paste tailings resulting from mineral processing activities (Fan et al. 2022). Tailings dams can be fragile structures, and too often, they are subject to liquefaction (Carrera et al. 2011). Stacking compacted filtered ore tailings is a promising alternative for safer tailings disposal. Filtered tailings are the disposal technology most likely to yield an unsaturated state of the tailings. (Oldecop and Rodari 2020). However, adding more safety to the disposal of tailings is essential, especially in the current context where climate change increases the number of extreme precipitation events (Schnaid 2020). The dry stack tailings are built on compacted layers; therefore, the procedures adopted during this process are similar to those traditionally used in earthworks. The suitable design of these tailings' storage facilities must define an acceptable range of degree of compaction and water content to ensure its security. However, the influence of the compaction condition of dry stack tailings on hydraulic conductivity still needs to be better understood.

Hydraulic conductivity is a relevant design parameter in evaluating the water flow in porous media (Yang et al. 2012). The TSF's internal drainage systems must be designed appropriately to avoid excessive seepage pressure, saturation, and slope failure. Accurate calculation of the iron tailings permeability cannot be obtained by classical equations, such as Terzaghi's, Hazen's, and Kozey's (Gan et al. 2019). In that regard, some authors proposed analytical and numerical models to estimate the hydraulic conductivity of tailings (Gan et al. 2019, Fan et al. 2022). Structure and degree of compaction are essential factors affecting the hydraulic conductivity of tailings (Gun et al. 2019).

Another critical factor is the effect of the confining pressure applied on the conductivity hydraulic of compacted materials (Shafiee 2008, Dafalla et al. 2015, Dos Santos and Esquivel 2018). This factor is especially relevant for high-height dry stack tailings design.

Hundreds of meters of high piles are expected to be built in Brazil in the coming years (Consoli et al. 2022). On the other hand, only some studies have investigated the effect of the confining pressure on the conductivity hydraulic of the filtered tailings.

Accordingly, the present work studies the hydraulic behavior of compacted filtered ore tailings retrieved in a dry stack located in Minas Gerais state, Brazil. The investigation described in this paper evaluates the effect of the initial compaction and the applied confining pressure on hydraulic conductivity using a flexible wall permeameter.

2. Experimental design

2.1. Tested material

The material used in this study is filtered iron ore tailings obtained from a Tailings Store Facilities (TSF) disposal on trial dry stacking, collected in Minas Gerais state (Brazil). This material presents similar indices to many iron ore tailings produced in this country.

Table 1 shows the index data for the tailings studied. The gradation from sedimentation analysis is shown in Fig 1. This material corresponds to a non-plastic sand-silt iron ore tailing; it has 52% < 0,075 mm and a D_{50} of ~ 0,070 mm. The minimum and maximum void ratios are 0.510 and 1.284, respectively.

Table 1. Index properties

Property	Value
Specific gravity, G_s	2.986
Liquid plasticity, w_P	NP
Fine particles content, % < 0,075 mm, Fc	52%
Mean grain size, D_{50} (mm)	0.070
Maximum void ratio, e_{max}	1.284
Minimum void ratio, e_{min}	0.510

This research determined the maximum and minimum void ratios according to the Japanese Geotechnical Society Standard (JGS-011 2009). According to this guideline, e_{max} was determined by pouring material into the mold using a funnel and lifting it at a constant rate, and e_{min} was obtained by dividing the dried sample into nearly equal part 10 parts (layers) and compacting each layer with 100 impacts on the side of the mold. Even though this procedure is suggested for sand presenting a small fine fraction (5% or less passing through on a sieve with an aperture width of 0,075 mm), some authors use the Japanese Standard for more significant fine content (Gobbi et al. 2022, Mijic et al. 2021). In addition, many authors have adopted e_{min} and e_{max} to aid in the characterization of non-plastic sand-silt mixtures (Zlatovic and Ishihara 1995, Thevanayagam et al. 2002, Carrera et al. 2011, Torres-Cruz and Santamarina 2020). This material has high fines content because of its production process, but does not have clay minerals.

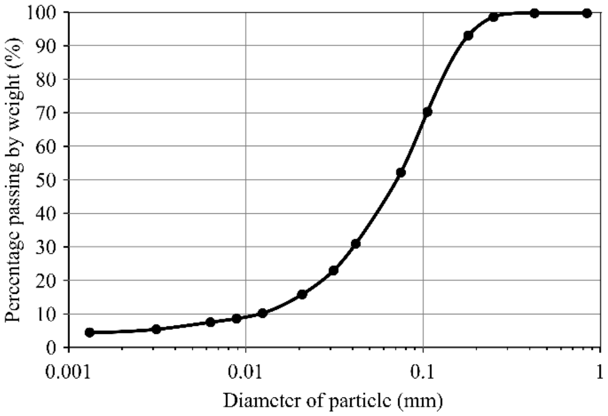

Figure 1. The particle-size distribution curve of the tailings studied.

Fig 2 displays the compaction curves obtained from modified and standard Proctor tests, determined by ASTM D1557-12 (ASTM 2021) and ASTM D698-12 (ASTM 2021), respectively. The maximum dry density and the optimum water content values obtained for these tests are shown in Table 2. It is observed that the maximum dry density in the modified test is higher than in the standard test, and the optimum moisture content is lower in the standard test. Even though the optimum water content in modified and standard tests are different, the peaks of these curves are located near the dashed line corresponding to a saturation degree equal to 60%.

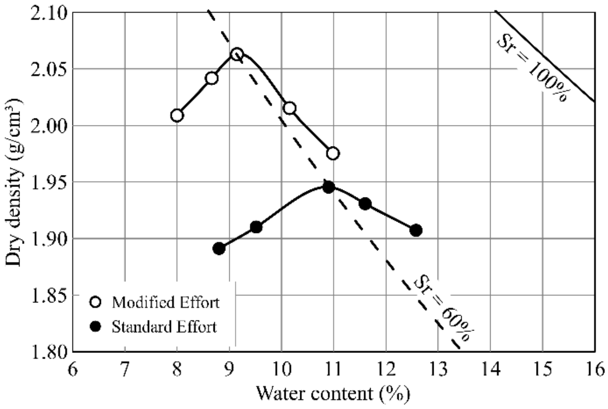

Figure 2. Standard and modified Proctor test results of the tailings studied.

Table 2. Comparison of standard and modified Proctor test results

Property	Standard	Modified
Maximum dry density (g/cm³)	1.945	2.062
Optimum water content (%)	10.9	9.2
Void ratio, e	0.535	0.448

In Table 2, it is possible to observe that the void ratio obtained by standard Proctor compaction is similar to the minimum void ratio determined by the JGS method, while the void ratio obtained by the modified test is approximately 11% lower than the minimum void ratio determined by the JGS method. Numata et al. (2002) investigated the minimum void ratio of several silty sands using different compaction energies. These authors suggested that e_{min} value could be determined using standard compaction test apparatus employing 10 to 15 times more energy than the standard Proctor compaction test, denoted in this way by the $e^*_{\min}$. For higher compaction energy, the authors observed crushing in the soil particles. Based on these findings, Ishihara et al. (2016) considered it necessary to correct the $e_{\min}$ value for silty sand containing fines, according to data shown in Fig 3. These data show that the $e^*_{\min}$ obtained by the standard Proctor with more energy added is considerably smaller than the $e_{\min}$ obtained by the JGS method. Ishihara et al. (2016) observed that the ratio $e^*_{\min}/e_{\min}$ tends to decrease and converges to a value of 0.7 when the presence of fines exceeds 30%. Fig 3 also displays the values of void ratios obtained by the JGS method, modified and standard compaction test in the iron ore tailings studied in this research. The void ratio values obtained in this study are close to each other; however, the maximum energy used in the present work is lower than the compaction energy used by Numata et al. (2002). The energy applied by modified compaction is only 4.5 times more than that used in the standard proctor compaction test. Therefore, further studies with higher compaction energies are needed to assess the need to correct the minimum void ratio of the tailings studied.

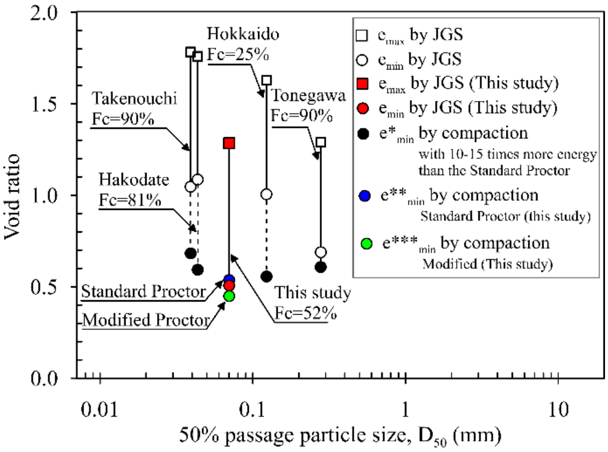

Figure 3. Change in a minimum void ratio depends upon the method of compaction and tailings of the present study. Adapted from Ishihara et al. (2016).

2.2. Sample preparation

Tailings compacted specimens were reconstituted in the laboratory by moist tamping method, adding about 10% of the water of the total sample dry weight. The specimens were compacted in a cylindrical mold of 50 mm in diameter and 100 mm in height. The specimens were prepared using three different degrees of compactions to evaluate the effect of increased compaction effort on hydraulic behavior. The selected degrees of compaction are listed in Table 3. These compaction conditions represent a range between the loosest and densest conditions.

The relative density (Eq. 1) depends on the specimen's void ratio and the maximum and minimum void ratio. Table 3 displays the relative density equal to 37, 84, and 98%. According to Michell and Soga (2005), the competitiveness states for these relative densities correspond to lose, very dense, and very dense, respectively.

$$D_r = \frac{e_{\max} - e}{e_{\max} - e_{\min}} \tag{1}$$

Where:

e is the current void ratio of concern;

$e_{\max}$ is the maximum void ratio;

$e_{\min}$ is the minimum void ratio.

Table 3. Degree of compaction of the specimens performed in this study

Test Specimens	Degree of compaction (%) Standard	Degree of compaction (%) Modified	Void ratio	D_r (%)
77S	77	73	0.996	37
94S	94	89	0.635	84
101S	101	95	0.525	98

Table 3 shows that the high relative density obtained in specimen 101S indicates that the standard Proctor effort was sufficient to bring its void index to a value close to the minimum void index ($e_{\min}$), determined by the JGS method.

2.3. Hydraulic conductivity test procedure

The hydraulic conductivity tests were performed in a flexible-wall permeameter, according to ASTM D5084-16a (2016) – Method A (constant head). The process of saturation of each specimen was achieved in three steps. First, carbon dioxide gas (CO_2) was circulated upwards in the specimen. The main objective of this procedure is to remove the air within the specimen and replace it with CO_2. From the use of CO_2 is possible to achieve the full saturation condition of cohesionless soils faster than other saturation methods (Jefferies and Been 2015, Viana da Fonseca et al. 2021). After this step, de-aired water was circulated inside the specimen to increase its degree of saturation. Finally, the back pressure increment method was adopted to dissolve tiny air bubbles in the pore water. To check the test specimen's saturation, the pore pressure coefficient B-value was measured, as defined by Skempton (1954). The B-value was considered satisfactory when it was greater than 0.98.

After the saturation process, each specimen was isotopically consolidated under confining pressure of 100 kPa, 200 kPa, 400 kPa, 800 kPa, 1600 kPa, and 2200 kPa. Subsequently, the percolation of de-aired water through the specimen was started using a low hydraulic gradient of about 5. During the hydraulic conductivity test, the inflow and outflow volumes were measured over time, and the hydraulic conductivity was calculated. The test was carried out until four stable hydraulic conductivity values were obtained. In this test, the hydraulic conductivity was calculated by Eq. (2).

$$k = \frac{Q \times L}{t \times A \times \Delta h} \tag{2}$$

where:

Q is the quantity of flow, taken as the average of inflow and outflow, cm;

L is the length of the specimen, cm;

t is the time elapsed in the flow stage, s;

A is the cross-section area, cm^2;

Δh is the head loss across the specimen, cm.

3. Results and discussion

3.1. Influence of initial compaction on normal compression line

The isotropic compression data were examined to assess the effect of initial compaction on the compressibility of the tailings studied and to see whether this material presents transitional behavior or not. Transitional soils are soils for which initial fabric dominates its behavior (Mayne et al. 2009).

These data for the tested specimens are given in Fig. 3. These results were plotted in the v: ln(*p*') space. The initial specific volume, v_i, was calculated using Eq. (3). Those points were fitted by a linear model and their adjusted parameters are present in Table 4. These results indicated that normal compression lines (NLC) strongly depend on initial compaction. Some authors showed that the NCLs of sands with different initial compaction converge to a unique normal compression line only at high pressure (Croop and Lee 1993, Consoli et al. 2005). The lack of convergence of NCLs from different initial compaction conditions must reflect the stability of the initial fabric that cannot be broken down by compression alone (Mayne et al. 2009). The parallel NCLs may suggest transitional behavior for tailings (Velten et al. 2022). This behavior often is associated with significant particle breakage (Consoli et al. 2005). Thus, the results shown in Fig. 4 indicate no considerable particle breakage in the stress range tested. However, additional tests under higher confining pressures are needed to confirm these conclusions.

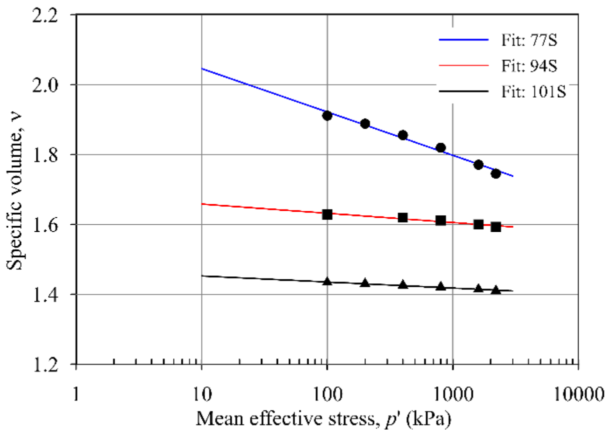

Figure 4. Isotropic compression lines.

$$v_i = \frac{G_s \times \gamma_w}{\gamma_{di}} \tag{3}$$

Where:
G_s is the specific gravity;
γ_w is the water weight;
γ_{di} is the initial dry unit weight.

$$v = \lambda \ln p' + N \tag{4}$$

Where:

N is the volume intercept at 1 kPa of a straight normal compression line; *λ* is the gradient of a straight normal compression line.

Table 4. Adjusted parameters of normal compression lines

Test specimens	λ	*N*	R^2
77S	-0.053	2.170	0.981
94S	-0.011	1.684	0.945
101S	-0.007	1.470	0.981

These data also show that the higher specific volume sample has steeper compression paths; even so, convergence with the lower specific volume paths does not occur. Shipton and Coop (2015) observed a trending behavior in the sand with non-plastic fines.

3.2. Influence of confining pressure on hydraulic conductivity

Fig. 5 shows the effect of confining pressure on hydraulic conductivity. From these data, it is possible to observe that the increased confining pressure decreases the hydraulic conductivity. These results support the idea that hydraulic conductivity is a function of confining pressure, which agrees with what was observed by Dafalla et al. (2015). It is found that the hydraulic conductivity decreases by less than one order of magnitude, regardless of the initial compaction. Moreover, the data suggest that hydraulic conductivity's decay rate depends on initial compaction. The decrease in hydraulic conductivity can be attributed to a reduction of the void ratio caused by an increase in confining pressure (Shafiee 2008).

As observed in Fig. 5, there is a relationship between increasing confining pressure and decreasing hydraulic conductivity. However, the decreasing void ratio under the confining pressure of 1600 kPa and 2200 kPa was not enough to significantly reduce the hydraulic conductivity value. Thus, under high-stress confining, the hydraulic conductivity becomes practically constant.

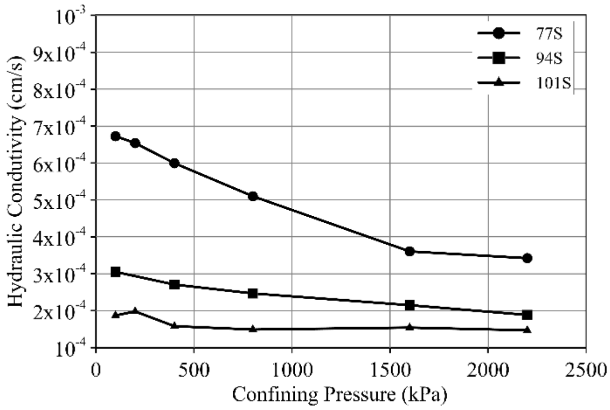

Figure 5. Effect of confining pressure on hydraulic conductivity.

Fig. 6 shows the relationship between hydraulic conductivity and the void ratio of the specimens. The results indicated that for each initial compaction, there is a linear relationship between hydraulic conductivity and void ratio. In the two very dense specimens (94S and 101S), the increase in confining pressure generated a slight reduction in the void ratio. Thus, the small drop in the void ratio observed in the very dense specimens did not contribute to the pronounced decrease in hydraulic conductivity. In other words, in denser specimens, the confining pressure has a minor influence on hydraulic conductivity, which agrees with what was observed by Bandini and Sathiskumar (2009) in sand-silt mixtures.

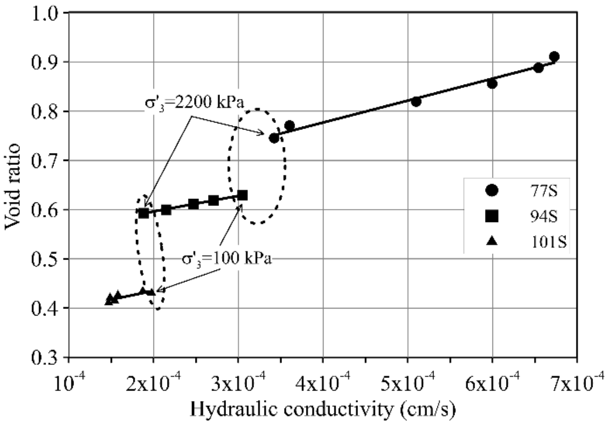

Figure 6. Effect of void ratio on the hydraulic conductivity.

It is important to mention that only the void ratio is not enough to characterize the hydraulic behavior of compacted tailings. It is observed from the points inside the dashed ellipses that different void ratios developed similar hydraulic conductivity. These results are probably associated with the effect of the initial compaction, indicating that the hydraulic behavior of the tested specimens is entirely dependent on the initial fabric.

4. Conclusions

Saturated hydraulic conductivity tests were carried out on a compacted non-plastic sand silty tailing. The effect of initial compaction and of the confining pressure was investigated. The normal compression lines depend on initial compaction and did not achieve a single line at the stress level studied, demonstrating that in this stress level the initial fabric is still important for the material behavior. More research studies are required in tests with higher stress.

The increase in confining pressure decreases the hydraulic conductivity. The results indicate that the hydraulic conductivity of the loose specimen decay at a greater rate than in dense specimens. Densest specimens are less likely to decrease hydraulic conductivity, even when high confining pressure is applied.

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