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Quality of reconstituted tailings samples based on their mechanical response

João Oliveira[1], *Paulo* Coelho[2], and *Luís* Araújo Santos[3]

[1]*University of Coimbra, Civil Engineering Department, joaopsvo@hotmail.com, Portugal*
[2]*Univ Coimbra, CITTA- Research Centre for Territory, Transports and Environm., Civil Eng. Dep., pac@dec.uc.pt*
[3]*Polytechnic Institute of Coimbra, Coimbra Institute of Engineering, CITTA, SUScita, lmsantos@isec.pt*

ABSTRACT

With a growing global population and greater environmental awareness modern societies inevitably need more mineral resources. Thus, an increase in mining activity is expected through the reactivation of old mines and/or the licensing of new explorations. Increased mining operations will lead to the production of higher volumes of tailings that often endanger people and the environment.

To suitably assess the behaviour of tailings, it will be necessary to carry out a complete and exhaustive laboratory characterisation in order to determine the necessary parameters for the correct sizing of the tailings disposal structures. In this sense, for a successful laboratory work, it is necessary to obtain good quality intact or remoulded samples for testing and comparison. However, good quality intact samples of tailings are rarely available. Therefore, reconstituted samples assume an important role. Currently the most commonly used reconstitution methods for mine tailings are the moist tamping and slurry methods.

This paper aims to discuss the potential of the most commonly used sample reconstitution methods in mine tailings. Some mechanical characterisation studies of tailings are also presented, namely when subjected to monotonic and cyclic stresses, with the aid of triaxial and oedometer equipment. Complementary tests with unusual equipment, such as Hollow Cylinder Apparatus (HCA) and bender elements, are also presented. Finally, and in view of the research carried out, the main limitations in laboratory tests carried out on these materials are identified.

Keywords: Tailings; reconstituted samples; element tests; Hollow Cylinder Apparatus, Bender elements.

1. Introduction

Minerals and metals play a fundamental role in the history of humanity and in today's society, in the implementation of clean energies used today, namely in wind turbines, solar panels and electric vehicle batteries. As the energy transition evolves, traditional fossil fuel systems are replaced by renewable energy, implying greater consumption of minerals. As such, the 2030 Agenda has 17 Sustainable Development Goals (SDGs), composed of 169 targets, targeting the environment, society, economy, and institution (UN, 2016). Minerals and metals will play a key role in the process of energy transition to a more sustainable low-carbon society. Therefore, the demand and exploitation of these materials will inevitably increase in order to implement this transition (World Bank, 2017). Fig. 1 shows the increasing demand for minerals required for cleaner energy. Two scenarios of developments are indicated. A first, more conservative scenario (Scenario 1), based on current policies, indicates that by 2040 twice as many minerals will be needed as are used today. The second scenario, which is based on the Sustainable Development Goals presented in the Paris agreement in 2015, indicates that by 2040 four times more minerals will be needed than are currently used. As a result, it is clear that in any of the scenarios presented it will be necessary to increase the exploitation of minerals and metals significantly.

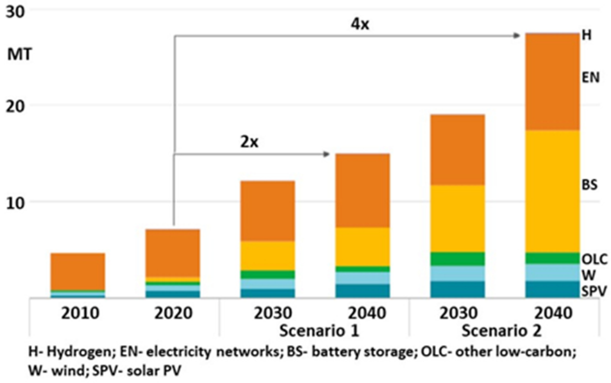


Figure 1. Minerals needed for clean energy by 2040 (adapted from USAID, 2021).

The mining industry produces huge volumes of tailings. As mining increases, the volumes of tailings from mining will increase significantly. Normally, these tailings are deposited in retention structures called tailings dams, which have considerable dimensions and are composed of unconventional geomaterials whose physical and mechanical characteristics are poorly known. As such, there is a risk of these structures rupturing and causing huge environmental, social and economic impacts (Kossoff et al., 2014).

Unfortunately, history shows that many of these dams have suffered very serious accidents for various reasons. If at the moment there is a problem due to major failures with serious environmental, human and social consequences, that problem may increase in the future. The way forward must be to promote research in this area to better understand the behaviour of these materials under different loading conditions.

2. Basic properties and mine tailings

In general, depending on the type of ore, tailings may contain particles of quartz, mica, chlorite and pyrite among others, quartz particles being the largest (Mlynarek, 1995).

2.1. Dry density and in-situ voids content

The in-situ void ratio of mining tailings can generally range from 0.6 to 1.4. This great variability can be explained by the type of tailings. If the tailings are similar to sand, the void ratio can vary from 0.6 to 0.8, but if they are in the form of mud, the void ratio can vary from 0.9 to 1.4 (Volpe, 1979). Therefore, when the tailings have higher water contents, they tend to have higher void ratios and, consequently, lower dry density. The inverse situation happens when the tailings present lower water contents. This conclusion is relevant for the preparation of reconstituted samples through slurry deposition, in which, by varying the amount of water used to prepare the slurry, it is possible to adjust the value of the void ratio and thus obtain values identical to those that can be found in-situ.

2.2. Relative density

For characterization of the initial state of granular soils, the relative density is a very important aspect to take into account. This is related to the maximum ($e_{\text{máx}}$), minimum (e_{min}) and natural void ratio, and can be calculated as a function of both the void ratio, and the dry density of the soil (Araújo Santos, 2015), as shown in Equations 1 and 2. The three main factors on which in-situ relative densities depend are dry volume weight (γd), the type of tailings (sands or fines) and grain size. The relative density of tailings is, according to Vick (1990), between 30% and 50%.

$$D_r = \frac{e_{max} - e}{e_{max} - e_{min}} \times 100 \tag{1}$$

$$D_r = \frac{\gamma_{d,max} \times (\gamma_d - \gamma_{d,min})}{\gamma_d(\gamma_{d,max} - \gamma_{d,min})} \times 100 \tag{2}$$

2.3. Solid particle density

Typical solid particle density values of mining tailings range from 1,6 to 5. It is notable that there is some variability in values, which shows that this property is dependent on the type of ore exploited (Bhanbhro, 2017). In the case of iron ore tailings, values of around 3.2 are obtained, while copper ore tailings present values of around 2.6, very close to the typical values shown by sands (2.65) (Volpe, 1979; Hu et al., 2016).

2.4. Particle size

The grain size distribution curve of tailings is determined by the disaggregation process and the type of ore. Particle size is the main property that, together with compaction, controls the hydraulic conductivity (Witt, 2004). This variation is due to segregation and sedimentation during tailings deposition (Witt, 2004). Sand in tailings is defined as the largest particles, generally occupying about 15% to 50% of the tailings structure (James, 2009). However, the grain size distribution may vary from mine to mine depending on the grinding process used (Vick, 1990). It should also be noted that the coarser particles of the tailings are often very angular in shape (Mlynarek, 1995).

Considering the factors that influence the characteristics of tailings, and directly affect their grain size distribution, MEND (2017) presented a granulometric classification that can be seen in Table 1. By analyzing Table 1, it can be seen that tailings can vary between granular and ultrafine tailings, presenting characteristics from a silty sand to a silty clay, depending on the mineral that is extracted.

Table 1. Physical classification of mining tailings (adapted from MEND, 2017)

Tailings Type	Symbol	Description	Examples
Coarse tailings	CT	Silty sand, non-plastic	Salt, mineral sands, coarse coal wastes, iron ore sands
Hard rock tailings	HRT	Sandy silt, non-plastic to low plasticity	Copper, massive sulphide, nickel, gold
Altered rock tailings	ART	Sandy silt, trace to some clay-sized particles, low to moderate plasticity	Porphyry copper with hydrothermal alteration, oxidized rock
Fine tailings	FT	Silt, with trace to some clay-sized particles, low to moderate plasticity	Fine coal waste, bauxite residue (red mud)
Ultra-fine tailings	UFT	Silt clay, high plasticity, very low density and hydraulic conductivity	Oil sad, phosphate fines, some kimberlite and coal fines

2.5. Consistency limits

Liquid limit values for mining tailings vary between 21% and 75%, while plasticity index vary between non-plastic and 60% (Quille et al., 2010). The mining tailings are materials that present low plasticity values, since the typical grain size distribution curves of tailings present low percentages of clay. However, tailings containing higher percentages of clay, as is the case with coal tailings, may present higher plasticity (Puri et al., 2013; Islam et al., 2021).

The natural water content of tailings usually vary in the range 20 to 67% (Quille et al., 2010; Hu et al., 2016). The tailings with higher water content have low consistency and high void ratios.

3. Sample preparation with mine tailings

Obtaining high quality samples in mine tailings is a challenge due to the need to maintain the integrity of the soils and the possible changes in their structure arising from the sampling, transport and extrusion processes in the laboratory. Changes in the relative density or structure of the samples affect the interpretation of the results obtained in laboratory tests and may make them less representative of the real field conditions (Ramos et al., 2021). Thus, the collection of high-quality samples is essential for the accurate characterisation of soils and for the determination in advanced laboratory tests of the strength and stiffness properties of these materials (Viana da Fonseca et al., 2017).

If it is not possible to take intact samples, it is necessary to prepare quality samples, which is probably the most important stage in the study of the mechanical behaviour of soils (Araújo Santos, 2015). Ideally, the reconstitution methodology should faithfully reproduce the in-situ deposition process, and the quality of this reproduction is measured by comparing the soil structure in the field with the structure of the reconstituted specimen (Serra et al.,1997).

3.1. Preparation of reconstituted samples

The tests performed on granular samples, such as tailings, are usually performed using reconstituted samples due to the difficulty in obtaining intact samples and the costs associated with the required techniques.

In general, the most commonly used methods in the laboratory are wet compaction, air pluviation and water pluviation (Corrêa and Filho, 2019). According to Vaid and Negussey (1988), rainfall methods are considered to be the techniques that best reproduce the process of natural deposition of sands in alluvial deposits. However, pluviation methods when used on sandy soils with fines may suffer from segregation problems (Kuerbis and Vaid, 1988). For this reason, their use in obtaining reconstituted samples of mining tailings may be quite limited, as they can be classified as sands with fines Vick (1990), Bedin (2012), Been (2016), or as transition soils between sands and clays (Li Wei, 2017).

A possible alternative to pluviation methods, to circumvent the problem of segregation of finer particles, can be the use of the moist tamping Reid et al. (2018) Raposo, (2016) and Schnaid et al. (2013). Another possible alternative to pluviation methods is slurry deposition method. This sample preparation technique, derived from pluviation in water, has been considered a technique capable of producing results close to reality, for natural alluvial soils and mine tailings (Corrêa and Filho, 2019). Therefore, the moist tamping and slurry deposition methods are presented in sections 3.1.1. and 3.1.2., respectively. Note that reference is made only to these methods of sample preparation because, they are the two most common methods in the literature for preparing reconstituted samples of mine tailings.

3.1.1. Moist Tamping

The reconstitution technique using moist tamping consists of depositing wet layers of material in the mould from a predetermined height that remains fixed throughout the process. Then, the deposited material is compacted with the appropriate frequency and energies to obtain the required voids content. This stage must be calibrated for each type of sample that is intended to be used (Ishihara, 1996).

Fig. 2 illustrates the reconstitution process using the moist tamping method.

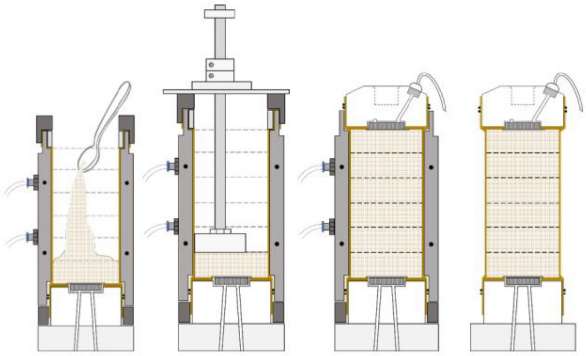


Figure 2. Reconstitution technique using moist tamping (adapted from Viana da Fonseca et al., 2021).

One of the advantages of this method is the ability to produce relatively homogeneous samples in very loose conditions with very high void ratios (Schnaid et al., 2013). However, if the compaction energy per layer is always the same, the lower layers ended up with a higher relative density than the uppermost layers (Ladd, 1978). The same author developed a method to overcome this difficulty, being used in the method presented by Viana da Fonseca et al. (2021). Another problem with the moist tamping method is that stratification of the sample can occur and thus does not represent the mode of deposition of the tailings under natural conditions (Schnaid et al.,2013).

3.1.2. Slurry method

The procedure of this technique was developed based on the method initially proposed by Kuerbis and Vaid (1988) for well-graded silt and clean sands. The main steps of this technique are summarised below (Carraro and Prezzi et al., 2008):

- Weight the required amount of soil and homogenise all the material.
- Place water in a cylindrical acrylic tube with a stopper at the bottom until half of the tube is filled. At the upper end, place the soil with the help of a funnel, which should enter the cylinder at a slow speed to minimize the appearance of air bubbles, as illustrated in Fig. 3a). After this process, remove the funnel and place water until the entire cylinder is filled. Finally, seal the upper end with a stopper.
- Shake the tube repeatedly up and down and simultaneously rotate it around a transverse axis (Fig. 3b). During this process, if needed, remove the stopper and add more water added in order to remove any air bubbles. This process is repeated enough times until no more air bubbles are present. Stir the measuring cylinder until the entire mixture is homogeneous, for a minimum time of not less than twenty minutes.

- At the end of this process, remove the stopper at the upper end must and place filter paper and a porous stone (Fig. 3c). Turn the beaker, as shown in Fig. 3c), so that there is suction and the filter paper and porous stone seal the bottom of the beaker. Place the assembly vertically into the mold with the membrane, which contains water (Fig. 3d) and left to stand for approximately twenty minutes (Fig. 3e). This resting period is necessary so that the paste is sustained before removal from the measuring cylinder. Removing the cylinder prematurely may cause loss of the sample.
- After the resting time, remove the upper lid as well as the the thinner upper paste (Fig. 3f). Before removing the measuring cylinder, place a collar and fill it with water as illustrated in Fig. 3g). Then remove the cylinder and scrap the paste off the upper part of the collar (Fig. 3h).
- The last step, illustrated in Fig. 3i), consists of removing the collar and scraping the paste near the top of the mold.

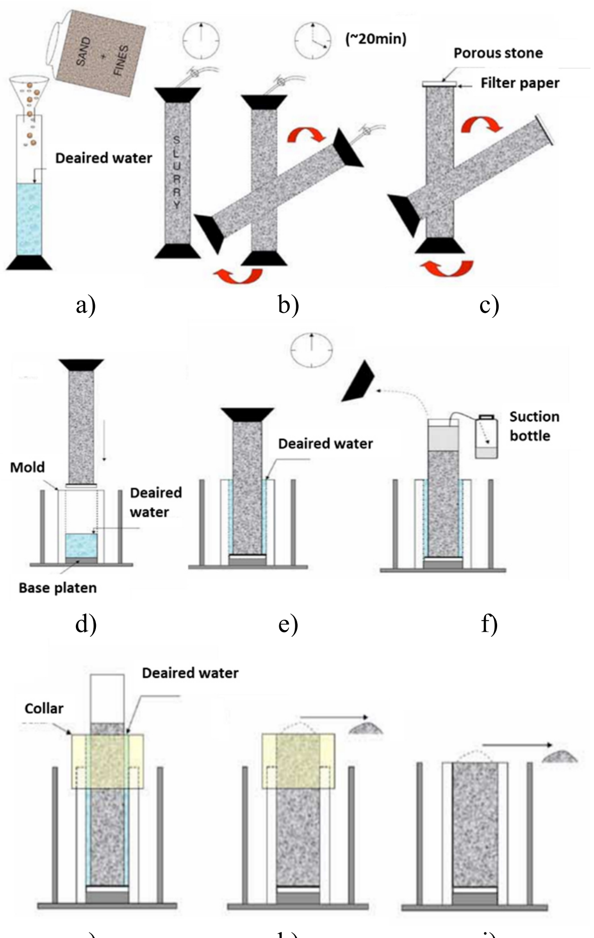


Figure 3. Technique schematic representation of slurry deposition method (adapted from Carraro and Prezzi et al., 2008).

An alternative version of the Slurry deposition (SD) method of reconstitution of solid triaxial specimens of sands with fines proposed by Carraro and Prezzi (2008) was developed to allow reconstitution of uniform hollow cylinder specimens of clean and non-plastic silty Ottawa sands with a high initial degree of saturation (Tastan and Carraro et al. 2013). Hollow cylinder specimens formed had nominal height, outer diameter, and inner diameter equal to 200, 100, and 60 mm, respectively. Briefly, the proposed SD technique consists of (1) forming a slurry by mixing de-aired water with a homogenous dry mixture of sand (with or without silt), (2) transferring the slurry into the annulus formed between two polycarbonate concentric mixing tubes with length and thickness equal to 711 and 3 mm, respectively (the outer diameters of the inner and outer mixing tubes were 70 and 95 mm, respectively), (3) placing the concentric mixing tubes filled with the saturated homogenous slurry into the annular space formed between the inner and outer hollow cylinder molds , and (4) carefully raising the concentric mixing tubes to allow the slurry to deposit inside the hollow cylinder mold annulus. During step (4), specimen disturbance was minimized by avoiding tube tilting and shaking. This procedure produced loose specimens of clean and non-plastic silty sands with initial DR of around 25 %–30 %.

4. Current laboratory characterisation of tailings behaviour

4.1. Compressibility and consolidation in oedometer tests

Mine tailings are more compressible when compared to natural soils with equivalent grain size, due to their granulometric characteristics, their deposition in the loose state and high angularity (Vick, 1990). According to some authors, tailings are generally considered to be normally consolidated, with rare cases of over-consolidation (Vermeulen, 2001). Primary consolidation in tailings with sandy characteristics happens very quickly, and its measurement in the laboratory is very difficult (Witt, 2004). According to Vick, (1990) the variations of the consolidation coefficient for sandy tailings are in the order of 5×10^{-5} to 10^{-6} m^2/s and for paste from 10^{-6} to 10^{-8} m^2/s.

Fig. 4 indicates the relationship between the void ratio and the vertical effective stress of various types of tailings, with coarser and finer grain sizes.

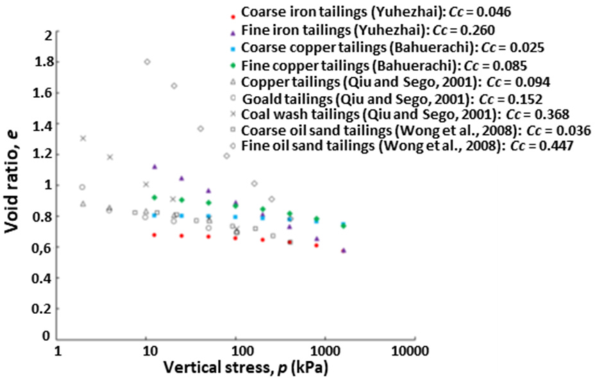
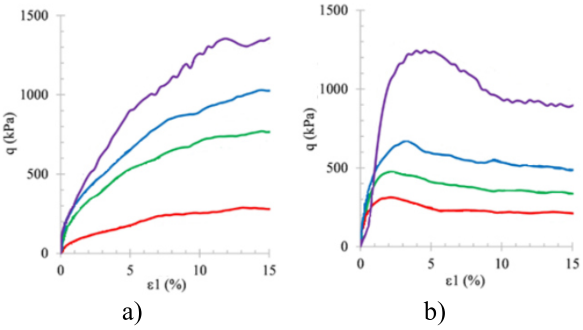


Figure 4. Void ratio versus logarithm of vertical stress (adapted from Hu et al., 2016).

4.2. Drained and undrained behaviour under monotonic loading in triaxial equipment

Silva et al. (2022) performed a set of drained triaxial tests on iron ore tailings. The tests focused on samples, loose and dense, reconstituted by the wet compaction technique. As it was expected, the higher the initial effective stress, higher is the peak strength. In Fig. 5a) for the loose samples it is possible to observe that the samples contract until they reach a plateau, which corresponds to the maximum deviatior stress. The dense samples, represented in Fig. 5b), show a peak of the deviator stress, which corresponds to the point of maximum shrinkage. After reaching the peak, the resistance decreases with increasing stress, reaching a residual stress, which remains constant.



a) b)

Figure 5. Deviator stress – axial strain graphs of drained triaxial tests with iron ore tailings for: a) loose specimens; b) dense samples (adapted from Silva et al. 2022)

Through a set of undrained triaxial tests, Bedin et al. (2012) evaluated the mechanical behaviour of tailings from a gold mine. According to the authors, the material is characterized as a silty sand without plasticity. The results illustrated in Fig. 6 demonstrate that a peak in the deviator stress occurs up to strains roughly equal to 5%, followed by a decrease in the deviator stress. The decrease in the deviator stress after the initial peak occurs when the shear force required to balance the soil is greater than the shear strength of the soil. Through Fig. 6, it is also possible to verify that all samples present a positive pore water pressure when subjected to shear stresses, revealing a contractive response in most of the presented tests.

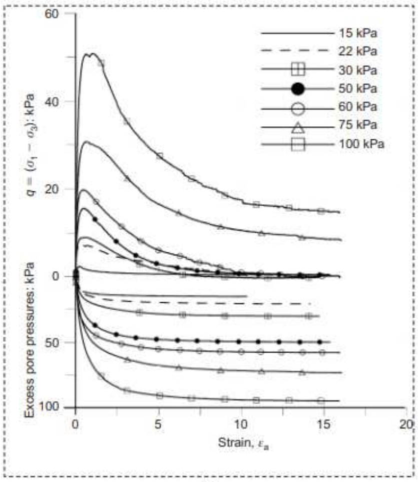


Figure 6. Undrained test results, effective stress, strain and excess pore pressure (adapted from Bedin et al., 2012).

4.3. Undrained behaviour under cyclic loading in triaxial equipment

Suazo et al. (2016) performed a set of cyclic triaxial tests with tailings from a zinc mine. In general, when a soil is subjected to cyclic loading, it exhibits hysteretic cycles. In these tests it was possible to verify that the sample suffered liquefaction by cyclic mobility, that is, as the loading cycles progress, the sample suffers a decrease in stiffness and consequently an increase in pore water pressure (Suazo et al., 2016). With the increase in the number of cycles the distortion value will naturally increase.

5. Advanced laboratory characterization

5.1. Hollow Cylinder Apparatus

Direct simple shear (DSS) represents a key loading condition influencing slope stability (Jardine and Smith 1991; Ladd, 1991). The DSS simple shear test is used to assess the behaviour of geomaterials under simple loading conditions.

An alternative to DSS tests and triaxial tests is the Hollow Cylinder Apparatus (HCA). It should be noted that carrying simple shear tests on HCA is not straightforward and a summary of the most usual techniques is presented by Araújo Santos (2015). The basic principle of operation of the HCA is based on the independent combination of the following efforts/ pressures: an axial load, torsional moment, internal pressure, external pressure and back pressure on a hollow cylindrical specimen (Hight et al., 1983; Vaid et al., 1990; Guo et al., 2016; Araújo Santos, 2015). A more comprehensive explanation of the HCA features and controls is beyond the scope of the present publication. At this moment there are few published works using HCA in mining tailings.

Fanni et al (2022) prepared hollow samples of low plasticity gold ore tailings using the moist tamping method. In Fig. 7 are presented the stress-strain results between DSS tests and torsional tests with the HCA and in Fig. 8 the normalized vertical effective stress as a function of horizontal shear stress.

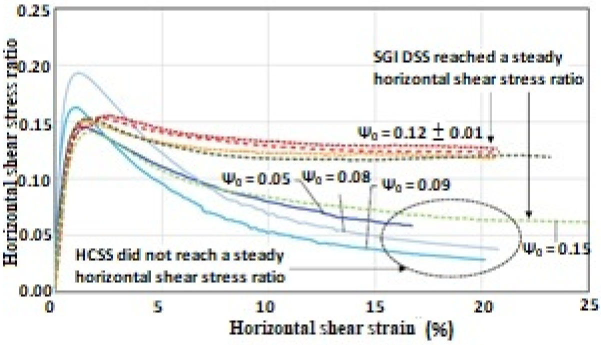


Figure 7. Shear strain against horizontal shear stress ratio (adapted from Fanni et al., 2022).

From the analysis of Fig. 7 the peak horizontal shear stress ratio in the torsional (HCSS) tests in HCA increases with increasing K_0, which can be attributed to the different initial anisotropic stress conditions applied to the samples (Ladd, 1991; Imam et al., 2002). The DSS tests have a peak horizontal shear stress rate similar to HCSS1 (K_0=0.5) and HCSS2 (K_0=0.75) tests. This may suggest that the samples from the simple direct shear tests (DSS) have a coefficient at rest (K_0) ranging between 0.50 and 0.75. This range of K_0 seems plausible for a consolidated specimen under a lateral deformation condition of zero, as in the simple shear test (Fanni et al., 2022).

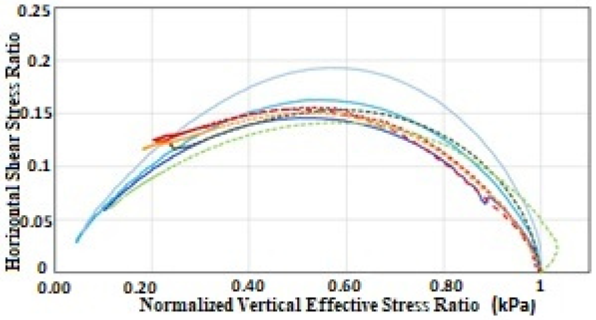


Figure 8. Normalized vertical effective stress against horizontal shear stress ratio (adapted from Fanni et al., 2022).

5.2. Bender Elements

The use of bender elements for determining the initial stiffness has gained a prominent place due, not only to its simplicity of execution and reduced cost, but also thanks to obtaining the G_0 practically directly. Its use dates back to 1978, by Shirley and Hampton (1978), although only after the publication of results by Dyvik and Madshus (1985) did the method gain general acceptance, and since then it has been widely used for the determination of initial stiffness. Another great advantage of this equipment is that, given its simplicity and small size, it can be installed in common triaxial cells, allowing the effect of the confining pressure applied to the samples to be studied in a simple way.

Through direct shear tests with sandy gold tailings, Riveros et al. (2020) implemented bender elements in order to measure the velocity of the shear waves. In this work the variation of V_S with σ'_{vc}/Pa increases not only with an increase in σ'_{vc} but also with a decrease in e_c of for a given σ'_{vc}. These results agree with other published data (Mantegh 2006; Schnaid et al. 2013). To account for the strong effect of σ'_{vc}, V_S is often expressed as a normalised overburden shear wave velocity (V_{S1}).

As illustrated in Fig. 9, V_{S1} measured in the sand tailings of this study, as well as those of other gold tailings (Grimard 2018; Schnaid et al. 2013) traces on the liquefied (left) side of this boundary. This is consistent with the observed instability and stress softening behaviours of the same tailings specimens in constant volume DSS (Riveros et al. 2020 study) and undrained triaxial compressional shear (Grimard, 2018; Schnaid et al., 2013) tests. Whereas the triaxial compression shear tests on sand and mud gold tailings tested by Mantegh (2006) generally show dilated stress paths, and V_{S1} of these specimens plot mainly on the unliquefied (right) side of Fig. 9. Although this liquefaction limit is developed for the sand tailings from the Riveros et al. (2020) study, as described above, it appears to apply to other sand and silt tailings as well (Grimard 2018; Mantegh 2006; Schnaid et al. 2013).

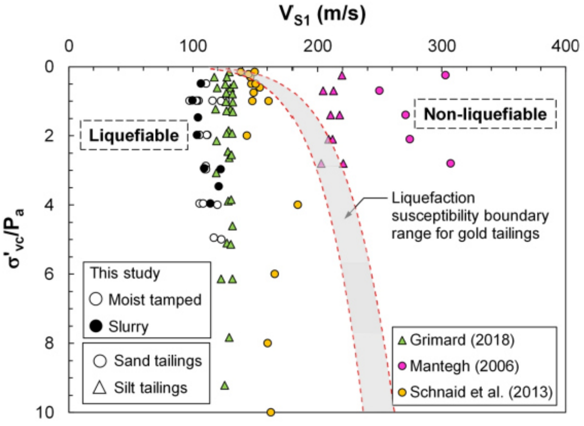


Figure 9. Comparison of the Vs-based liquefaction susceptibility boundary range with V_{s1} measured in the gold tailings (adapted from Riveros et al., 2020).

6. Conclusions

Tailings storage facilities located around the world are becoming an increasingly serious problem due to current risks to society and the environment. Recent accidents around the world coupled with a growing demand for minerals and metals to support a transition to a low carbon economy is increasing the pressure on the mining industry to assess the behaviour of these materials?? (Been, 2016; Li Wei, 2017). In view of these aspects, it is essential to carry out standard and advanced laboratory characterisation of mine tailings in order to obtain parameters that can be used in suitable design of the structures for the disposal of these materials, so that in the future accidents such as those that occurred in the Fundão and Brumadinho dams in Brazil in 2015 and 2019, respectively, can be avoided. This paper aims to present the main methods of preparation of samples reconstituted from mining tailings, as well as to present several laboratory tests that aim to deepen the mechanical knowledge of these materials. The same material may have completely different results, depending on its deposition method, as well as the distance from the discharge point. In this sense, the method of preparation of reconstituted samples plays an important role in the quality of the results obtained. The performance of advanced tests, such as HCA and bender elements, enables a deeper understanding of the mechanical behaviour of these materials. The lack of information with this type of tests promotes their use as well as new lines of research. In this sense, the following points are highlighted:

- The mechanical behaviour of mining tailings subjected to monotonic and cyclic conditions under undrained conditions was essentially established from experimental studies carried out with triaxial equipment, there being a deficit of work with hollow cylinder specimens;
- The use of equipment that allows performing torsion tests on hollow specimens is not frequent in this type of material. Therefore, the Hollow Cylinder Apparatus (HCA) appears as an option to

the conventional triaxial equipment. The advantages of HCA in allowing independent control of the magnitude of the three principal stresses, as well as the possibility of rotating principal and minimum stresses, allow the study of their influence on the mechanical behaviour of mining tailings, which, depending on the location of the dam or heap to be analysed, will have different principal stress directions;

- The highly variable grain size distribution of these materials is associated to the drainage capacity, which can result in a more or less drained behaviour, being directly related to the reasons of the origin of failures in retaining structures;
- The study of the morphology of these materials, which are similar in size to soils but do not behave like soils, is very unique. These materials present angular and rough particles that may confer greater fragility, being a case study to be investigated;
- The influence of the sample preparation method on the undrained strength, starting from different values of K_0, indicates that the limits of stable behaviour are not the same, which reveals a dependence of these laws on the resting state condition and, therefore, on the inherent anisotropy that cannot be ignored.

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