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# Adaptations to a triaxial equipment for testing of mine tailings

*Nuno Raposo*[1#], *Roberto Olivera*[2], *Ricardo Bahia*[3] and *António Topa Gomes*[4]

[1] *Construct / Instituto Politécnico de Viseu, Viseu, Portugal*
[2]*Golder Associates, Vancouver, Canada*
[3]*Golder Associates, Porto, Portugal*
[4] *Construct /Universidade do Porto, Porto, Portugal*
[#]*Corresponding author: npraposo@estgv.ipv.pt*

## ABSTRACT

Mine tailings are usually materials with particle sizes in the range of silts, frequently exhibiting very low consistency. This low-consistency condition poses challenges when trying to reconstitute specimens for triaxial testing. The first part of this work presents a description of the main geotechnical properties of mine tailings used in the tests and the difficulties associated with triaxial testing. Next, some developments, in terms of equipment and testing procedure, are presented: the design of a compaction mould, the specimen preparation using moist tamping and the lubricated end platens. Finally, the process of dismantling the specimen using freezing is presented and discussed. The final part of the paper presents some results and summarizes the challenges associated with adapting the equipment and implementing the testing procedures.

**Keywords:** Triaxial, Mine tailings, Specimen preparation.

## 1. Introduction

The production of mine tailings as a by-product of ore extraction is inevitable, containing a high percentage of the material extracted from the ground. All the by-product generated is considered waste and must be deposited and stored adequately. During many years, mine tailings were deposited without control, creating critical situations for the environment and public health (Blight 2009). In many cases, economics limit the resources necessary to develop or improve sustainable practices in the mining industry. Consequently, the mine tailings are commonly managed using conventional methods of deposition inside mud containing reservoirs, while cement and materials extracted from other locations are used to fill underground tunnels and galleries that have been abandoned. However, more recently, there has been an increase in the number of mine sites where the tailings are processed in order to reuse in engineering applications (Jewell 2010). Examples include the reuse of process water, as well as using tailings for underground fill.

Scientific and engineering advances have provided an enormous contribution to the efficient and productive mine tailings management. As a result, regulators have been licensing more holistic approaches to mine waste water management problems, one of which is the paste tailings deposition (Jewell and Fourie 2015).

The physical, chemical and mechanical properties of the mine tailings are directly related to the processing they are subjected to, from the ore extraction until the deposition phase. Although there may be variations in extraction methodology, these processes are common to

most mining operations (Vick 1990). Such operations modify the particle size distribution and also the mineralogy of the tailings. Therefore, it is important to carry out tests to characterize their geotechnical properties, which are required in the use of the best design practices for disposal and deposition in ways that consider public safety and environmental impacts.

In addition to standard index testing, such as specific gravity, grain size distribution, and Atterberg consistency limits, it is essential to characterize mine tailings in terms of their hydraulic conductivity, compressibility and strength. The latter can be measured in the triaxial cell, allowing the definition of the friction angle, cohesion, stiffness, compressibility and critical state conditions. The following sections present recommendations for modifying the standard triaxial testing equipment that would facilitate specimen reconstitution overcoming the problem of handling low consistency samples, while at the same time improving the quality of the results with particular emphasis on the measurements of properties at the critical state.

## 2. Geotechnical properties of the tailings

Typically, mine tailings have particle size distribution equivalent to natural silts, with varying percentages of sand and clay-sized particles. Despite their similarity to natural soils, in terms of particle sizes and their distribution, their hydro-mechanical and chemical behaviour differ considerably. As a result of their production from industrial processes, tailings tend to consist of particles with sharper edges, resulting in higher friction angles and higher susceptibility to crushing when subject to high confining stresses.

When tested in the laboratory, tailings are challenging to handle as they exhibit low to zero cohesion and due to their high compressibility and low hydraulic conductivity, they are prone to liquefy. The small hydraulic conductivity can cause difficulties when reconstituting samples that are saturated. They are also challenging to sample in situ, as they generally have very low consistency, which, combined with high compressibility, makes it almost impossible to obtain good quality undisturbed samples without resorting to more sophisticated sampling techniques, like ground freezing (Viana da Fonseca and Pineda 2017). Tailings also differ from natural soils in terms of specific gravity and chemical reactivity. Both these properties are highly dependent on the type of ore from which the tailings were produced.

It is important to note that tailings can be very reactive and may contain chemicals that can cause harm if not handled appropriately. Therefore, it is essential to have information about the chemistry of the materials to be tested beforehand, usually in the form of a Materials Safety Datasheet (MSDS). In any case, when working with mine tailings, it is a best practice to avoid contact with the skin by using gloves and always to wear a breathing mask. Taking bauxite tailings as an example, they can be highly alkaline with a pH ranging from 10 to 13 (Schmitz 2014). In this case aluminium instruments and containers should be avoided. Preferably stainless steel, brass or plastic shall be used.

## 3. Equipment and testing procedure

### 3.1. Lubricated end platens

The use of lubricated end platens is essential to reduce the influence of platen restraint on stresses in the specimen and on uniformity of strains (Jefferies and Been 2015). Lubricated platens also reduce shear stresses that could form between the caps and the specimen ensuring that the stresses that are being applied to the specimen are indeed principal stresses. A simple system is illustrated in Figure 1. The lubricated end consists of two discs of standard triaxial latex membrane, with a thin layer of silicone grease sandwiched between them. The platens should ideally be some 5 mm larger in diameter than the specimen to allow uniform radial strains at the ends of the specimen. Naturally, the lubricating discs mean that a full-sized porous stone cannot be used. This is generally

not a problem as the drainage provided by the proposed system has proven adequate. The one disadvantage is that estimating the hydraulic conductivity during the consolidation phase is no longer possible, as the theory assumes permeable boundaries on the top and bottom of the specimen (Bishop and Henkel 1962) and this flow boundary conditions cannot be provided with smaller porous stones. Jefferies and Been (2015) recommend the use of 20 mm diameter porous stones for 76 mm specimens of sand. Naturally, when using filter paper, it should be the same diameter as the porous stone, otherwise, it would cancel the effect of the latex discs. The end platens must have an insert such that the porous stones protrude out of them the thickness of the two latex discs, so the final surface is completely flat. Figure 1b and Figure 1c show photos of both end platens equipped with latex discs and ready for receiving a specimen. Further details about this issue are provided by Viana da Fonseca et al. (2021).

### 3.2. Self-centering top cap with restricted rotations

Due to the soft consistency of the tailings, it was necessary to create a self-centring mechanism, that could also restrict rotations of the top cap during the several stages of the triaxial tests. The preliminary tests showed that the stiffness of the pipes connecting to the top cap was rigid enough to slightly bend the specimens causing them to become off-centred. As soon as the piston would start loading the specimens, the top cap would rotate, because of the eccentric loading, causing the specimens to fail by bending instead of shearing, as desired.

After several attempts, the prototype of Figure 2 was created. As can be seen in the Figure 2a and Figure 2b, both the piston and the top cap are chamfered, allowing for a certain misalignment when closing the triaxial cell. In Figure 2c another development can be observed. To allow a rough estimate of the shrinkage of the specimens during flushing and saturation, the tip of the piston was marked at every 1 mm. Note that prior to the shearing phase, the piston is locked in position, inside the top cap groove. The deformations can only be measured with the LVDT during the shearing phase.
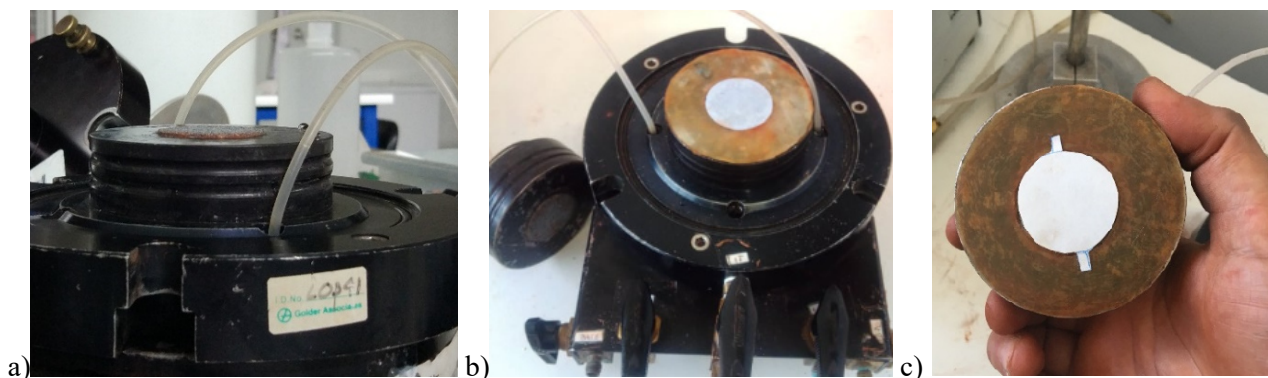


a) b) c)

**Figure 1.** Details of the lubricated end platens.

### 3.3. Compaction mould and moist tamping

To assist the preparation of specimens by moist tamping, a split mould and a compactor were manufactured, as shown in Figure 3. This mould has some peculiarities:

- the thickness of each of layer is defined prior to the compaction, by adjusting the stopper in the shaft. Independently of the force applied by the operator, the compaction is defined by the amount of tailings put in each layer;
- the inner diameter of the mould (71,8 mm) is smaller than the platens (76 mm), allowing the use of lubricated platens, as described previously;
- the design of the mould is provided with a protection system that enables the use of high compaction energy without damaging the membrane;
- the mould is longer than the specimen height, allowing the compaction of all layers identically;

- in the upper side of the mould there is a rim that allows the top plate to rest on the specimen without applying any load on it,
- all the inner edges of the mould were made blunt, in order to prevent any damage to the membrane.

With this mould, it is possible to prepare homogeneous specimens at the desired compaction (dense or loose) and thus obtain contractive or dilating specimens. To take into account the effect that the compaction of a given layer causes in the previous layers, the specimens are compacted with increasing quantities of tailings, from the bottom up. This approach, usually called the undercompaction method, was first proposed by Ladd (1978), and is particularly relevant in loose specimens. The mass of tailings to be used in each layer, $W_i$, can be calculated according to the following expression:

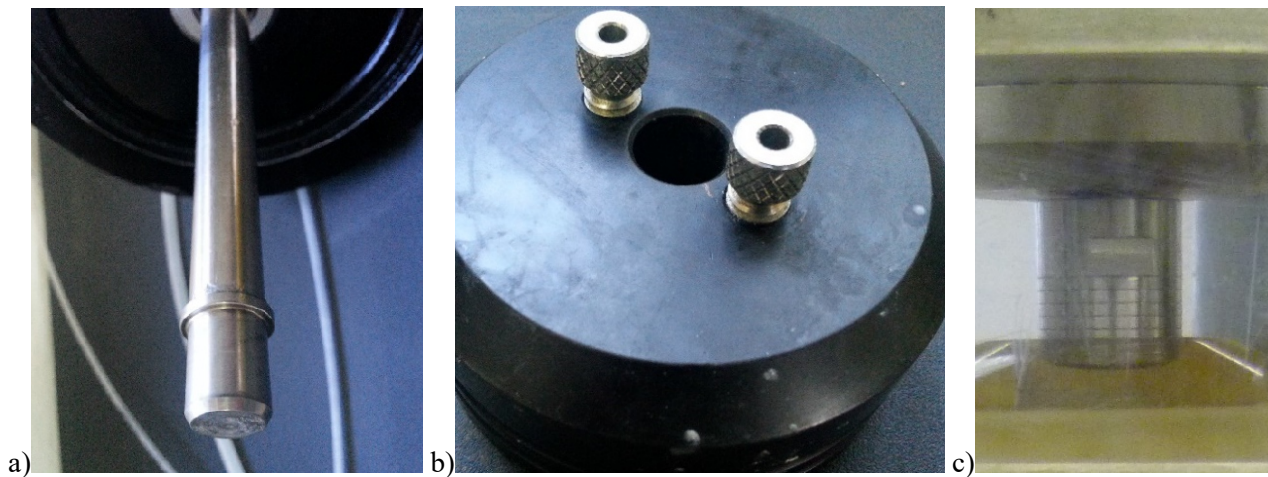$$W_i = \frac{Vol\ G\ (1+w)}{(1+e_0)\ n} \cdot \left( \frac{2\ U_n\ (i-1)}{1-n} + 1 + U_n \right) \tag{1}$$



a)                          b)                          c)

**Figure 2.** Details of the pistons and self-centering top cap with restricted rotations.



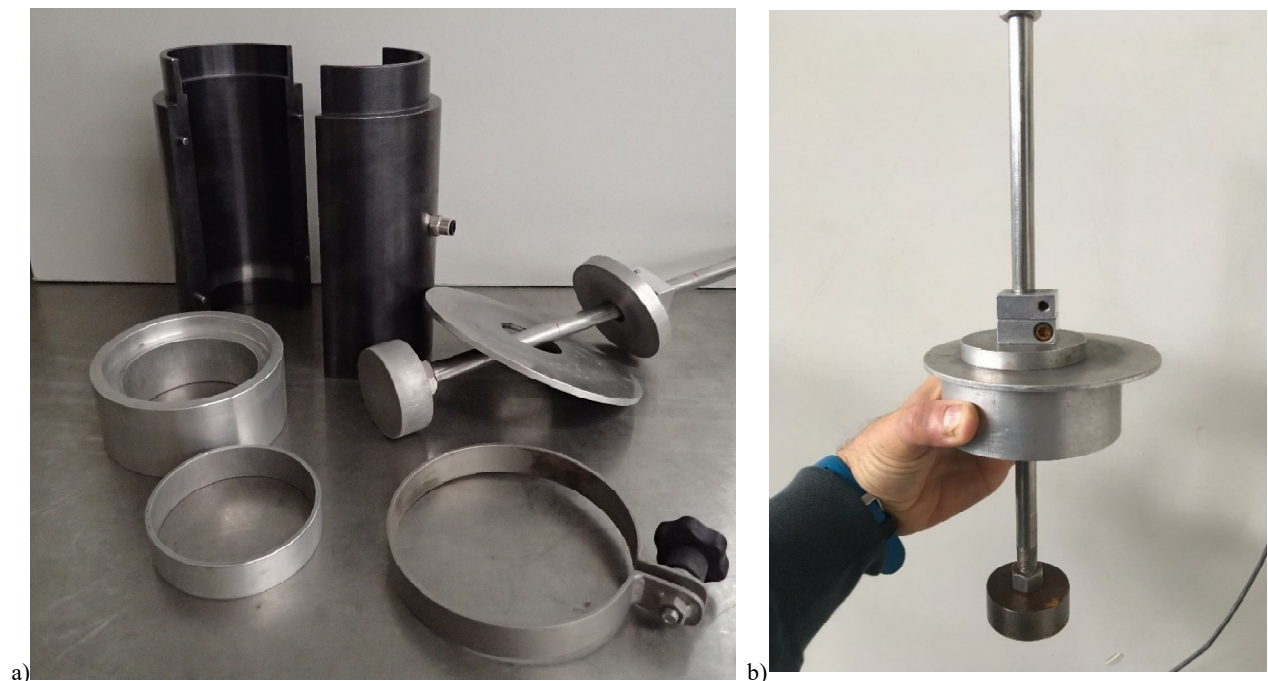a)                                              b)

**Figure 3.** Mould and compaction hammer.

where: $Vol$ is the volume of the specimen; $G$ is the solid particles relative density; $w$ is the gravimetric water content; $e_0$ is the desired void ratio; $n$ is the number of layers; and $U_n$ is the undercompaction factor.

The undercompaction factor must be adjusted by trial and error, so there may be the need to run one or two trial tests before reconstituting the final testing specimen. Using an adequate value of $U_n$ means the compaction energy the operator applies to each layer will be similar. For the tailings used in this paper, a $U_n$ of 2% shown to be adequate for loose specimens ($e_0 \cong 1,4$), while for dense specimens ($e_0 \cong 0,7$) the best results were obtained when using $U_n = 0$.

Figure 4a illustrates the process of compacting a triaxial specimen. In this picture it is possible to observe the stop of the compactor, through which it is possible to control the thickness of the layers. Figure 4b shows the placement of the top cap. It is acceptable to press the top cap, as it rests on a rim of the mould and not on the specimen. Figure 4c shows the disassembly of the split mould. A close look at this picture shows that there are five faint horizontal lines, corresponding to the transition between layers. Figure 4d displays the final appearance of a reconstructed specimen ready to be tested. This picture shows the specimen is thinner than que pedestal

and top cap, allowing the radial expansion of the specimen, as described previously.

Figure 5 shows some details of the compaction mould. The picture Figure 5a shows that the mould rests on the base of the triaxial cell, in order to avoid damaging the membrane. The bottom of the mould is slightly larger than its central part, leaving space for the base o-rings. Figure 5b shows the top cap placed on the mould rim. The o-rings are already placed but can only be lowered to their final position once both halves of the mould are removed.

The water content to be used during the compaction of the specimen is highly dependent on the physical properties of the material in question. In the case of bauxite tailings, the ideal water content was found to be close to 15%. Values greater than 18% cause the material to stick to the compactor, creating an uneven surface (Figure 5c). In contrast, water contents lower than 13% makes the material powdery, precluding particle bonding. In the case of copper tailings, the ideal water content for moist tamping was found to be around 5% (Raposo 2016). In cases where it is difficult to obtain dilating specimens, a Proctor test can be performed to determine the optimum water content for compaction.
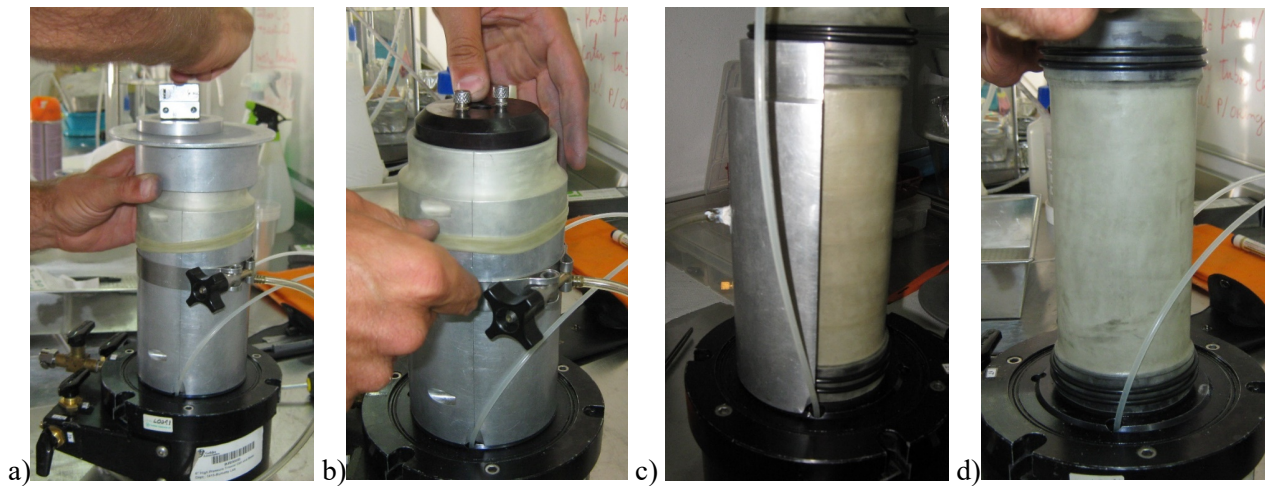
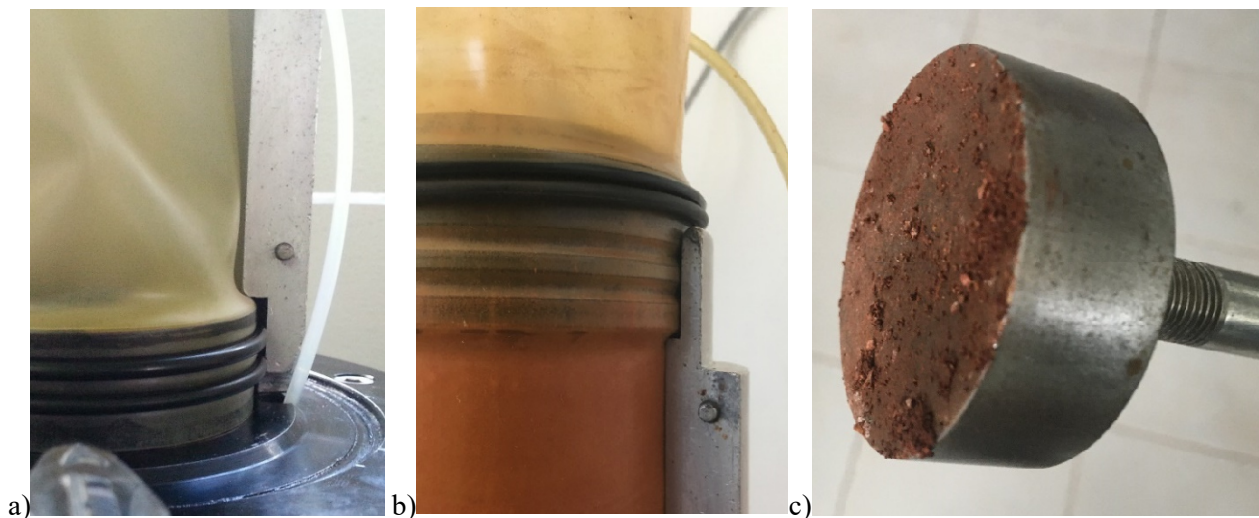

**Figure 4.** Preparing a specimen.



**Figure 5.** Details of the mould and compaction hammer

Prior to the compaction, the tailings were air-dried to the desired water content, broken up, homogenized, separated in portions of 1500 g, and stored in airtight bags. From these bags, subsamples were collected immediately before placing the first layer and immediately after the last layer, to determine water content and density or the tailings.

### 3.4. Measurement of the specimen dimensions

Theoretically, the diameter of the specimens corresponds to the inner diameter of the mould, corrected for the thickness of the membrane. However, it is essential to measure the real diameter of the specimen after removing the mould. The use of a calliper proved to be problematic, since it tends to create dents on the specimens, resulting in values lower than reality. To overcome this problem, measuring tapes were created, as illustrated in Figure 6a. As can be observed, the scale was printed with a resolution of 0.5 mm. In view of the proportionality between the perimeter and the diameter (3.1416), this marking allows measuring the diameter with a resolution below 0.16 mm. To ensure the tapes don't get wet from environmental moisture, they were wrapped in plastic cling. Before using the tapes, they must be calibrated to consider the distortion of the scale due to the curvature. Thus, using rigid specimens of known dimensions, a set of calibration factors, corresponding to each diameter, was determined (Raposo 2016).

### 3.5. Saturation process

The basic saturation process for specimens prepared dry or moist is that de-aired water is flushed through the specimen (always from bottom to top) to displace air. The water pressure is then increased gradually, which results in both a reduction of the volume of air due to compression and increased dissolution (Jefferies and Been 2015). In specimens with a large percentage of fines, however, this procedure might require longer times and higher back pressures.

An alternative method to reduce the time and backpressure needed for saturation is to flush carbon dioxide through the specimen prior to saturation. A low volume and pressure $CO_2$ source, controlled through a needle valve from a regular gas bottle and regulator, is connected to the lower platen water line. The $CO_2$ is flushed through the specimen after the top platen and membrane have been assembled, the mould removed, and nominal confining stress applied to the specimen. The $CO_2$ is vented through a thin tube from the top platen with its open end underwater to ensure that the $C0_2$ is passing through the specimen by observing the bubbles going out the tube. A bubble rate of 1 to 5 bubbles adequate, with the process lasting 1 to 2 hours (Jefferies and Been 2015, Lade 2016). This process can be controlled by collecting the $CO_2$ into an inverted bottle, initially filled with water, as shown in Figure 6b. Usually, 1500 cm³ of $CO_2$ and 300 kPa of back pressure are enough to achieve full saturation of the specimen.

Although this technique has proven to be very useful, it is necessary to pay attention to the reactivity of the tailings. It was found that the bauxite tailings react with $CO_2$, causing a reduction in volume. Figure 6c shows what happens when the tailings are poured into a bottle full of $CO_2$. In fact, this reaction has been investigated as a way of capturing $CO_2$ and simultaneously reducing the PH of the tailings (Sahu et al. 2010, Yadav et al. 2010).

### 3.6. Measuring the void ratio

Standard triaxial types of equipment, if equipped with submergible load cells, can measure stresses and vertical deformations relatively accurately. Measuring volume (or void ratio) changes, however, is not so straightforward. Changes in the void ratio occur in several stages of a triaxial test. During consolidation and shear phases, these changes can be measured by tracking the volume of water that is leaving or entering the specimen provided that it has been adequately saturated. The problem is measuring void ratio changes during the initial flushing and subsequent saturation phase. There have been advances in this field, such as the use of double-walled triaxial cells (Leong et al. 2004, Al-Sharrad et al. 2013), advanced image processing techniques (Bagherieh et al. 2008) and other sophisticated techniques, but they aren't usually available in a standard geotechnical laboratory.

A simple method for accurately determining the void ratio is by freezing the specimen. This technique, firstly introduced by Sladen and Handford (1987), has proven to provide accurate measurements of the void ratio (Reid et al. 2021). It consists of closing all valves immediately after the end of the shearing phase, dismantling the triaxial cell, and placing the cell base, together with the
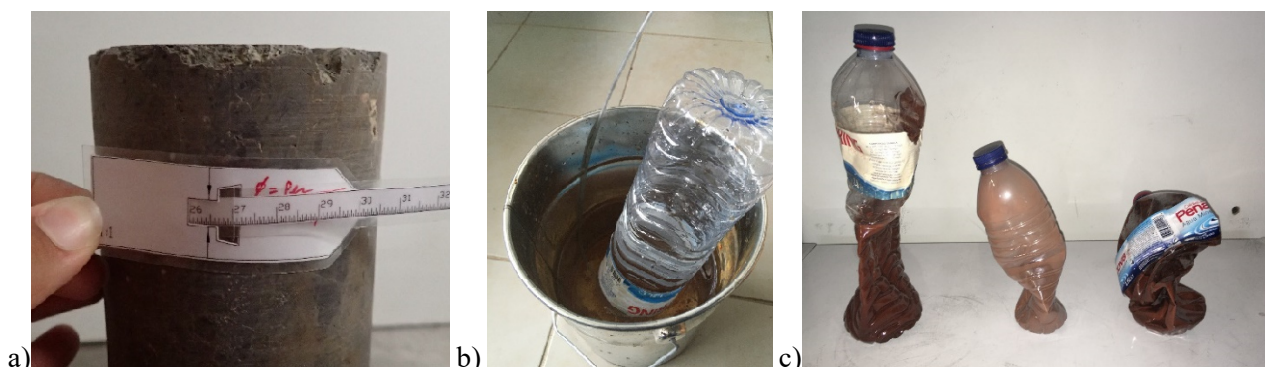


**Figure 6.** a) calibration of a measuring tape using a rock specimen; b) controlling the volume of $CO_2$ passing through the specimen; c) the reaction of bauxite tailings with $CO_2$.

specimen in the freezer. After the water becomes solid, the specimen can be removed from the cell without losing any water and weighted for water content, $w$, determination. This operation should be done quickly and in the driest possible environment, in order to prevent condensation, as can be seen in Figure 7, showing a frozen specimen immediately after being removed from the freezer. Assuming the specimen was completely saturated and measuring the specific gravity of the particles, $G$, the void ratio at the end of the shear phase can be determined by the equation (2). The void ratio variation during shear and consolidation can then be back-calculated using volume change measurements.
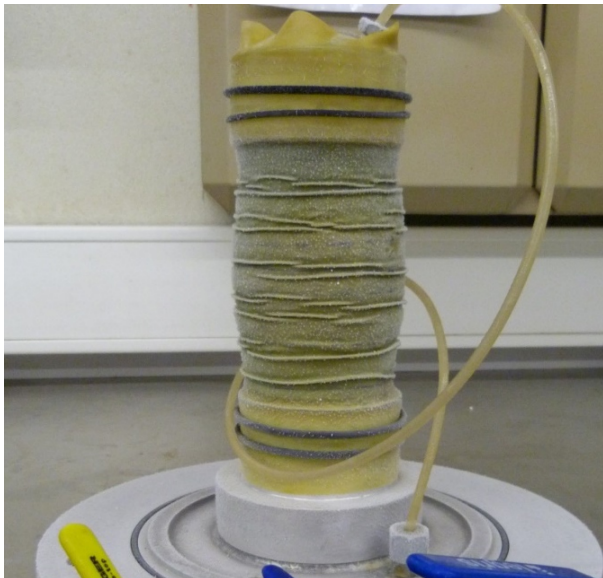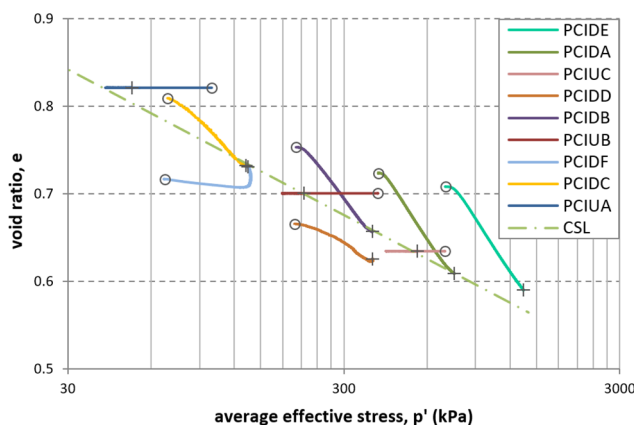
$$e = G.w \qquad (2)$$



**Figure 7.** Frozen specimen sitting on the cell base.

## 4. Typical results

The complete characterization of the tailings included several different triaxial tests, with varying drainage conditions (drained and undrained), several initial states (dense and loose specimens), and a wide range of consolidation stresses. As an example, Figure 8 shows the results obtained from a set of 9 triaxial tests performed on copper mine tailings, previously studied in terms of grain size distribution, specific density and consolidation (Raposo et al. 2019). The left graph of Figure 8 shows the variation of the void ratio during each triaxial test. The open circles mark the beginning of the shear phase and the crosses mark the end of the tests. The critical state line displayed was defined as the best fit for the values obtained at the end of the several tests. In terms of void ratio, the biggest difference from a single test to the defined critical state line is no bigger than 0.03. This difference can be regarded as a measure of the accuracy achieved with the tests. The right graph of Figure 8 presents the results of the tests in terms of average effective stress versus deviator stress. It shows the results are almost perfectly aligned, allowing a straightforward definition of the strength parameters (friction angle and cohesion).

## 5. Conclusions

The techniques described above have proven to be useful in performing triaxial tests. The compactor developed for this purpose made it possible to obtain high-quality homogeneous specimens, providing better control during the compaction process. The use of CO2 allowed to drastically reduce the time needed for the saturation phase. Lubricated and enlarged end-platens have proved to be useful. During the shearing phase, there was a noticeable reduction in the barrelling effect and in all tests, the radial expansion at the base and top of the specimens was notorious, which is not observed when non-lubricated platens are used.

The process of measuring the void ratio at the end of the shearing phase proved to be very simple and effective. It allows to obtain better results than the internal instrumentation, with the advantage of making the tests much simpler and faster.

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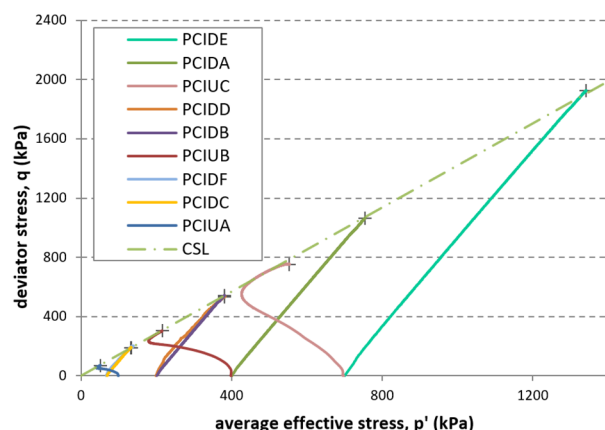
**Figure 8.** Triaxial test results in terms of strength and void ratio changes.

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